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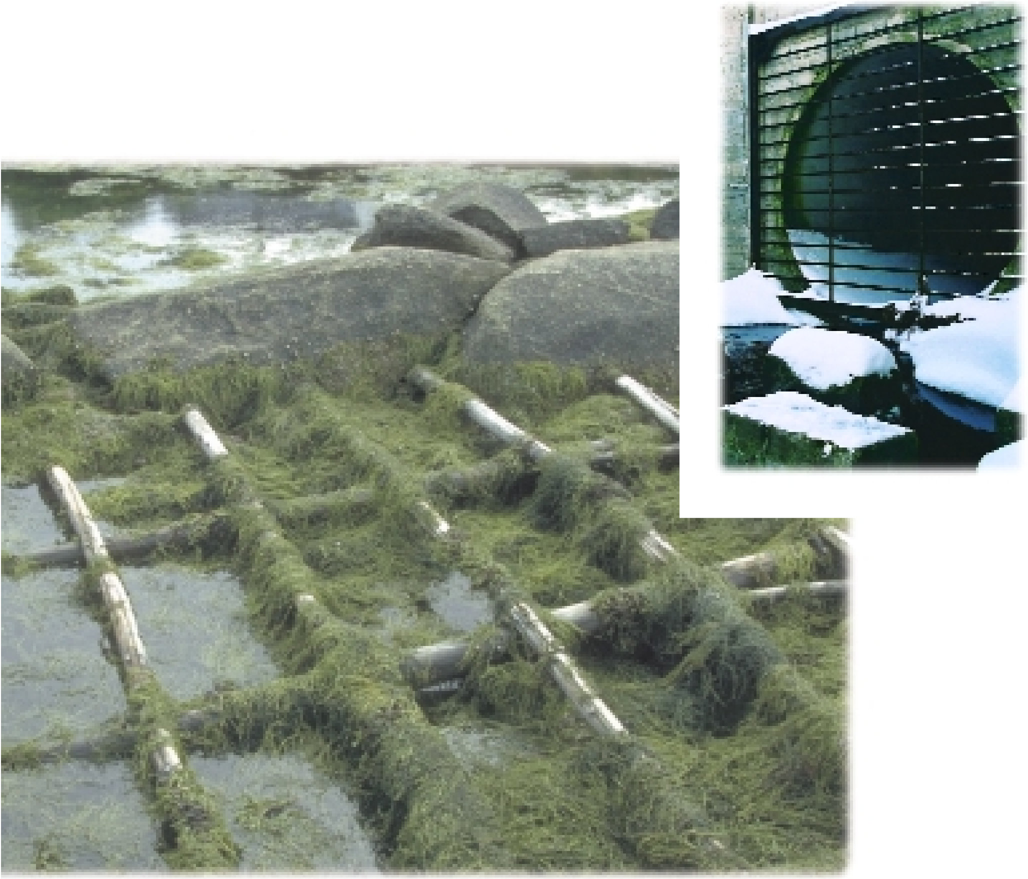
# NUTRIENTS IN THE CANADIAN ENVIRONMENT

## Reporting on the State of Canada's Environment



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# NUTRIENTS IN THE CANADIAN ENVIRONMENT

## Reporting on the State of Canada's Environment

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This state of the environment (SOE) report is a companion volume to the federal science assessment entitled *Nutrients and their Impact on the Canadian Environment*, which was authored by Patricia Chambers, Martha Guy, Elizabeth Roberts, Murray Charlton, Robert Kent, Christian Gagnon, and Gary Grove, all of Environment Canada, and Neil Foster of Natural Resources Canada. This SOE report is based on the data, research, and interpretation provided by the comprehensive science assessment, but set within an SOE approach.

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# Table of Contents

## List of Figures

## List of Tables

## List of Boxes

# Preface

Environment Canada issues state of the environment (SOE) reports for two key purposes: to provide Canadians with timely and accurate information, in a non-technical manner, about current environmental issues, and to foster the use of science in policy- and decision-making. In examining important environmental issues, the reports attempt to answer four key questions:

- **What is happening to the environment** (i.e., how are environmental conditions and trends changing?)**?**
- **Why is it significant** (i.e., what are the resulting implications for ecosystems, economic and social well-being, and human health?)**?**
- **Why is it happening** (i.e., how are human activities causing the environmental changes?)**?**
- **What is being done about it** (i.e., how is society responding to these concerns through government action, changes by industry, and voluntary initiatives to ultimately make progress towards environmental sustainability?)**?**

By serving these purposes and satisfying the content and presentation guidelines of the federal government's SOE reporting program, as approved by the five natural resource departments (5NR),[1] this report, *Nutrients in the Canadian Environment: Reporting on the State of Canada's Environment*, carries the SOE reporting symbol.

The report is intended primarily for policy- and decision-makers at all levels of government and private industry, including those involved in agriculture, aquaculture, and forestry, as well as water and wastewater management, to help them in making informed decisions about the management of nutrients in the Canadian ecosystem. It also serves to inform concerned Canadians, such as members of non-government organizations and community groups, educators and students, and the media, about the status and trends of one of Canada's top environmental issues — the release of nutrients in excessive amounts into the Canadian environment.

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[1] The 5NR departments are Agriculture and Agri-Food Canada, Environment Canada, Fisheries and Oceans Canada, Health Canada, and Natural Resources Canada.

The present report looks at how the Canadian environment is being affected by nitrogen and phosphorus compounds that are released as a result of human activities. These compounds are nutrients that, in excessive amounts, can overstimulate plant production, to the detriment of other species, in freshwater, saltwater, and terrestrial ecosystems. Some of these compounds are also associated with a variety of direct and indirect toxic effects on organisms, including humans. The report describes the mechanisms by which nutrients affect the environment, assesses their impact on the environment and their potential for future damage, and outlines the major sources of these compounds. It also looks at what has been done and what can be done to alleviate these problems.

This report is based on a science assessment, *Nutrients and their Impact on the Canadian Environment* (Chambers et al. 2001), that was the Government of Canada's response to the 1995 review of the *Canadian Environmental Protection Act* (CEPA). In the CEPA review, the House of Commons Standing Committee on Environment and Sustainable Development (1995) recommended that Environment Canada:

- regulate the phosphate content of cleaning agents other than laundry detergent under Part III of CEPA;
- determine whether further regulations are required for nutrients other than phosphates in cleaning agents; and
- determine whether sources of nutrients other than cleaning agents are adequately regulated by provinces and territories.

Those interested in a more extensive technical review of the issues presented here should consult the science assessment (Chambers et al. 2001).

# Highlights

Nutrients are elements or compounds that are essential to the growth and survival of organisms. The supply of nutrients within an ecosystem has a substantial influence on both the abundance of plant and animal life and the types and variety of species that can inhabit the ecosystem.

Expanding human populations and various human activities have greatly increased the biologically available supply of two key nutrients, nitrogen and phosphorus, in the environment. These nutrients, when present in excessive amounts, can overstimulate the production of plants, to the detriment of other species, and are associated with a variety of direct and indirect toxic effects on organisms, including humans.

The state of the environment (SOE) report on nutrients looks at how the Canadian environment is being affected by nitrogen and phosphorus compounds that are released as a result of human activities. The report describes the mechanisms by which nutrients affect the environment, assesses their impact on the environment, especially through enrichment, and their potential for future damage, and outlines the major sources of these compounds. It also looks at what has been done and what can be done to alleviate these problems.

At present, environmental problems caused by excessive nutrients are less severe in Canada than in many countries with a longer history of settlement and agricultural production. This is in part due to protective measures implemented by governments in the last 30 years. Nonetheless, while successes have been realized, environmental and human health problems related to nutrients are evident across Canada.

Highlights from the SOE report follow.

## What are the impacts of nutrient additions?

The impacts of nitrogen and phosphorus loadings in the Canadian environment include both effects associated with nutrient enrichment and the direct toxic effects of nitrogen compounds on aquatic and terrestrial organisms as well as humans.

## Enrichment effects

- In fresh waters, algal growth is often limited by the amount of phosphorus available, whereas the supply of nitrogen is generally the determining factor in ocean waters.
- Phosphorus loadings have accelerated the eutrophication, or overfertilization, of certain rivers, lakes, and wetlands, resulting in the loss or degradation of habitat and changes in biodiversity (e.g., changes in the types of bottom-dwelling organisms in lakes).
- Nitrogen loadings have caused local eutrophication in some coastal waters, including estuaries, which has led to a decrease in dissolved oxygen, a loss of habitat, and changes in biodiversity (e.g., an increase in nuisance algae).
- Some forest ecosystems have become saturated with nitrogen, which can leach to surface waters or groundwater and cause changes in soil chemistry, including nutrient imbalances.
- Nitrogen loadings have contributed to the acidification of soils and lakes in southern Ontario and Quebec.
- The aesthetic enjoyment of water may be impaired by turbidity, discoloration, foaming, and odour, and algae can restrict swimming, foul fishing gear, damage boat motors, and impede navigation.

## Toxic effects

- A number of fish kills related to nitrogen-containing discharges, particularly those associated with agricultural activities, have occurred in recent years.
- Nitrate is believed to be at least partly to blame for declines in amphibian populations in Canada. Adverse effects include poor larval growth, reduced body size, and impaired swimming ability.
- Nutrient additions have led to higher risks to human health from the recreational use of waters contaminated with toxic algal blooms and from the consumption of tainted shellfish.
- Concerns about water quality have increased because of taste and odour problems and the contamination of some water supplies with nitrate and algal toxins. The frequency and spatial extent to which the drinking water guideline for nitrate has been exceeded in groundwater across Canada have both increased.
- The economic burden to Canadians has increased as a result of the closure of shellfish fisheries, the need for treatment of contaminated water, and the need to transport household water from off-site sources.

# What are the principal sources of nutrients?

## Municipal and rural wastewater

- Municipal wastewater — largely human waste — is the largest point source of nitrogen and phosphorus releases to the Canadian environment. In 1999, about 82 750 tonnes of total nitrogen and 4 950 tonnes of total phosphorus were released to lakes, rivers, and coastal waters from municipal sewage.

- Nitrogen loadings to Canadian fresh waters from municipal wastewater treatment plants in 1999 were 24% higher than in 1983 as a result of population increases.
- Phosphorus discharges to fresh waters were 44% lower in 1999 than in 1983 due to the implementation of advanced phosphorus removal at many municipal wastewater treatment plants.
- The level of sewage treatment across Canada is generally improving, as more municipalities upgrade their wastewater treatment facilities. An exception is municipal wastewater discharged to coastal waters. Many communities are still served by primary treatment or none at all.
- About 8 million Canadians, slightly more than one-quarter of the population, are served by septic systems, which released an estimated 15 400 tonnes of nitrogen and 1 900 tonnes of phosphorus in 1996. If these nutrients cannot be assimilated by the receiving land, they can move into groundwater and, from there, to surface waters.

## Agriculture

- Nutrients in the form of chemical fertilizers and manure are applied to agricultural land to increase crop yields. In 1996, 1 576 000 tonnes of nitrogen and 297 000 tonnes of phosphorus as fertilizer were applied to cropland in Canada. In addition, 384 000 tonnes of nitrogen and 139 000 tonnes of phosphorus were applied as manure.
- Total nutrient additions (fertilizer, manure, nitrogen fixation by legumes, atmospheric deposition, application of sewage sludges, etc.) to agricultural land are substantially offset by crop uptake. For all agricultural land in Canada, annual nitrogen inputs for 1996 (2.8 million tonnes) exceeded outputs (2.5 million tonnes) by 10.7%.
- In 1995, the storage and handling of manure and fertilizer added 570 000 tonnes of nitrogen in the form of ammonia to the atmosphere.

## Industrial discharges

- An estimated 11 800 tonnes of nitrogen (as nitrate and ammonia) and 2 000 tonnes of total phosphorus are discharged annually to Canadian surface waters from industries with operating permits.
- Most light industries discharge their wastewater into municipal sewage systems for treatment at municipal wastewater treatment plants.
- Industrial emissions to the atmosphere in 1995 included 27 000 tonnes of nitrogen from ammonia, about one-third from industries manufacturing nitrogen fertilizers.

## Aquaculture operations

- Aquaculture operations release nutrients through the excretion of dissolved or solid waste by fish and from unconsumed feed. Cage finfish aquaculture in open water is of most concern, as wastes are released entirely to the surrounding water.

- The total Canadian finfish industry is estimated to contribute 2 276 tonnes of nitrogen and 486 tonnes of phosphorus to inland and coastal waters annually.

### Forestry

- Forests are the source of much of the water that enters streams and lakes. Forest management practices may increase concentrations of nutrients in streamwater. There is insufficient information at present to generalize about the impacts of forestry practices on dissolved nutrients in streams.

### Atmospheric emissions and deposition

- In 1995, 1 471 000 tonnes of various forms of nitrogen were emitted to the atmosphere, of which 608 000 tonnes (41.3%) were from the agricultural sector, 428 200 tonnes (29.1%) were attributable to fossil fuel combustion for transportation, and 329 400 tonnes (22.4%) were from industry (combustion-related emissions and industrial processes).
- Much of the nitrogen released into the atmosphere is redeposited on the ground or on water. In Canada, atmospheric deposition as a result of long-distance transport supplies approximately 2.5 kilograms per hectare per year in the form of nitrate and ammonium, the only two compounds of atmospheric nitrogen examined. Atmospheric deposition is considerably higher in eastern than in western Canada as a result of industrial activities in central Canada and the northeastern United States. Atmospheric deposition of nitrogen compounds contributes to both eutrophication and acidification of surface waters.
- Atmospheric phosphorus, much of it from fertilizer application and production, accounts for only 1–6% of the total phosphorus budget in Canadian lakes.

## What measures are being used to manage nutrients?

A wide range of measures has been developed in Canada to help control nutrient inputs into the environment.

### Municipal and rural wastewaters

- Some municipal wastewater treatment plants are required to employ advanced phosphorus removal before discharging their wastes to sensitive waters.
- Repair and replacement of sewage systems have reduced leakage and pollutant loadings.
- Conversion of combined sewer systems to separate systems or shunting of the most toxic first flush of stormwater into storage facilities/ponds for subsequent treatment prevents untreated sewage from entering surface waters.

### Agriculture

- The nutrient requirements of crops must be balanced by the supply of nutrients to the crops from the soil and from fertilizers. Most provinces have guidelines for manure application to soils, typically based on nitrogen application rates.

- Nutrient management strategies (e.g., transporting surplus manure from animal producers to crop farms) will improve farmers' abilities to manage nutrients more effectively, with the ultimate aim of reducing overfertilization.
- Livestock incorporate only 20–40% of the nitrogen and phosphorus originally present in feed. Technologies are now emerging for adding enzymes or other supplements to livestock diets to increase nutrient retention by livestock.
- In areas of intensive livestock production, treatment of animal waste could reduce the risk of contamination of surface water and groundwater by manure.

### Aquaculture operations

- Between 70 and 80% of nutrients added in aquaculture operations are lost to the environment as metabolic waste, feces, and uneaten food fragments. The development of more nutritionally balanced and digestible feed will reduce waste discharges from feeding.
- Environmental impacts associated with nutrient loss in aquaculture operations could be reduced by placing cages away from sensitive waters and shorelines, collecting and treating wastewater, and implementing good management practices.

## What information gaps need to be filled?

Data limitations constrain scientists' ability to assess changes in ecosystems due to excess nutrients. These are principally insufficient monitoring data on emissions and ambient conditions and insufficient knowledge as to the effects of nutrient additions on ecosystem and human health.

### Insufficient monitoring data

In attempting to define the status of Canadian ecosystems with respect to nutrients, data on sources and impacts are progressively less available as one moves from lakes to rivers/streams to wetlands to groundwater to coastal waters to forests. Some topics requiring particular attention are the following:

- Few nitrogen and phosphorus data are available for industries not connected to municipal wastewater treatment plants.
- Available data on nitrogen and phosphorus loadings for certain municipal wastewater treatment plants in Canada are not consistent in the parameters measured.
- Regional or national estimates of agricultural nutrient loadings to surface water and groundwater are not available, nor can estimates be obtained.
- Although estimates of atmospheric deposition of nitrate- and ammonium-nitrogen are available through a network of provincial and federal monitoring sites, similar data are not available for phosphorus or for total nitrogen, nor are estimates available for release from various sectors.
- Well water survey programs are patchy across the country.
- Reporting on fish kills from accidental spills/discharges of nutrient-related compounds is currently on a voluntary basis only.
- The potential impacts of climate change on nutrient loadings are poorly understood, as are the related measures to manage loadings.

## Effects of added nutrients on Canadian ecosystems

Additional research is required to understand the effects of added nutrients on Canadian ecosystems. Areas requiring particular attention are:

- the role of nutrients in inducing algal blooms and toxin production;
- the role of nutrients in causing taste and odour problems of drinking water supplies;
- transport and fate of nutrients within different ecosystems (wetlands, coastal waters, forests, rivers, and lakes) and effects on biota; and
- long-term and cumulative effects on the aquatic and terrestrial environment from the combination of several nutrient sources all operating within a region.

# What does the future hold?

Maintaining the quality of air, water, and soil environments with respect to nutrients is an important component of sustainable development. Yet studies have already shown that an overabundance of nitrogen compounds is overwhelming ecosystems in parts of the world. This nitrogen, in part from synthetic nitrogen fertilizers, can no longer be absorbed by terrestrial ecosystems and is ending up in rivers, lakes, groundwater, estuaries, and oceans.

Canada is in the position of being able to deal with nutrient pollution before it is overwhelming. Science-based solutions are available and new technologies are emerging that can assist in further reducing undesirable nutrient additions to the environment. Monitoring and research continue to be needed to ensure that decision-making is based upon sound science, and the best and most advanced science should continue to be integrated into practical solutions to maintain or improve the quality of Canadian air, water, and soil environments.

# 1

# Introduction

## What are nutrients?

Nutrients are elements or compounds of them that are essential for the growth and survival of organisms. Most living cells require large amounts of certain nutrients, such as nitrogen, phosphorus, carbon, hydrogen, oxygen, potassium, and calcium (macronutrients), but only small amounts of others, such as boron, manganese, copper, zinc, and chloride (micronutrients). Nutrients circulate in characteristic paths or cycles that involve exchanges between the organic and inorganic components of the environment as well as between plants and animals at every stage of the food chain. As it goes through its cycle, each nutrient element will be involved in a variety of chemical transformations that determine its availability to different organisms. The supply of nutrients within an ecosystem has a substantial influence on both the abundance of plant and animal life and the types and variety of species that can inhabit the ecosystem.

## What are the concerns about nutrients?

Expanding human populations and various human activities have greatly increased the biologically available supply of two key nutrients, nitrogen and phosphorus, in the environment. An oversupply of nutrients, a condition known as *eutrophication*, encourages excessive plant production in aquatic ecosystems. In lakes and rivers, increased plant productivity eventually reduces the oxygen content of the water, often to the point where fish and other species can no longer survive.

Phosphorus compounds are the main cause of eutrophication in freshwater ecosystems, but concerns have also been raised about increasing concentrations of nitrogen because of their contribution to the acidification of lakes and soils and their predominant role in the eutrophication of saltwater ecosystems. Excessive concentrations of some nitrogen-based nutrients, such as nitrates and ammonia, also can be directly toxic to plants and animals and can stimulate the growth of toxic algae in marine waters. Shellfish ingesting these algae can accumulate large amounts of toxins in their flesh, which, although they do little harm to the shellfish, can poison humans or other animals that eat them.

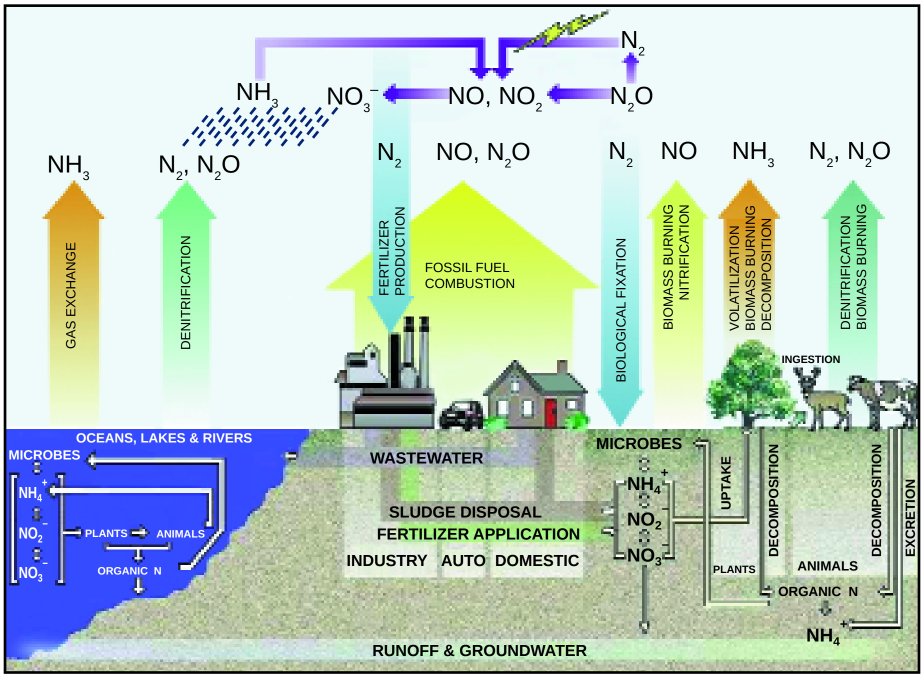
Nutrients first became a major environmental issue in the 1970s as a result of concerns about the eutrophication of Lake Erie. The implementation of controls on phosphates in laundry detergents and better sewage treatment helped to bring the problem under control. In various parts of the country, however, inputs of nutrients from other sources have increased to the point where further action may be necessary to protect some ecosystems from damage. Some nitrogen compounds also contribute to urban smog and global warming, although these issues will not be considered here.

## The nitrogen and phosphorus cycles

To understand how nitrogen- and phosphorus-based nutrients are accumulating in the environment, the natural nitrogen and phosphorus cycles need to be examined to determine how they have been altered by inputs from human activities.

Nitrogen is present in the atmosphere as nitrogen gas ($N_2$), nitric oxide (NO), nitrous oxide ($N_2O$), nitrogen dioxide ($NO_2$), and ammonia ($NH_3$) (Figure 1). In fact, almost 80% of the atmosphere is nitrogen, but almost all of this is in the form of nitrogen gas, which cannot be used directly by the vast majority of organisms. Before nitrogen can enter the food chain, it must be converted to a biologically reactive form. This is accomplished mainly by nitrogen-fixing bacteria, which convert nitrogen gas to amino acids and proteins. These bacteria include some of the blue-green algae (or cyanobacteria) that occur in water, some soil bacteria, and bacteria that live in the root nodules of legumes. When the plants die, other bacteria begin a process in which the fixed nitrogen is eventually converted to nitrates and ammonium ($NH_4^+$), which can be assimilated by other plants. Nitrates are also formed in the atmosphere when lightning discharges induce the formation of nitric oxide, which then reacts with oxygen to form nitrate ($NO_3^-$). Along with ammonium, nitrates eventually fall to Earth in rain and snow or as fine particles.

**Figure 1: The nitrogen cycle**



Source: Chambers et al. (2001), Figure 2.2.

Nitrogen in soils, water, and plant and animal material is returned to the atmosphere when nitrates are converted to nitrous oxide and nitrogen gas by microbes in soils and water, a process known as denitrification. Nitrogen in the form of ammonia is also released by evaporation from vegetation, soils, and animal waste, as a by-product of decomposition, and as a result of biomass burning.

Urbanization, industrialization, and intensive agriculture have altered certain portions of the natural nitrogen cycle. In particular, they have greatly increased the production of biologically reactive nitrogen, primarily through activities such as:

- fuel combustion, which adds nitric oxide to the atmosphere;
- the use of nitrogen fertilizers, which contain ammonia made from nitrogen gas; and
- the cultivation of legumes and other crops, which increases biological nitrogen fixation beyond natural levels.

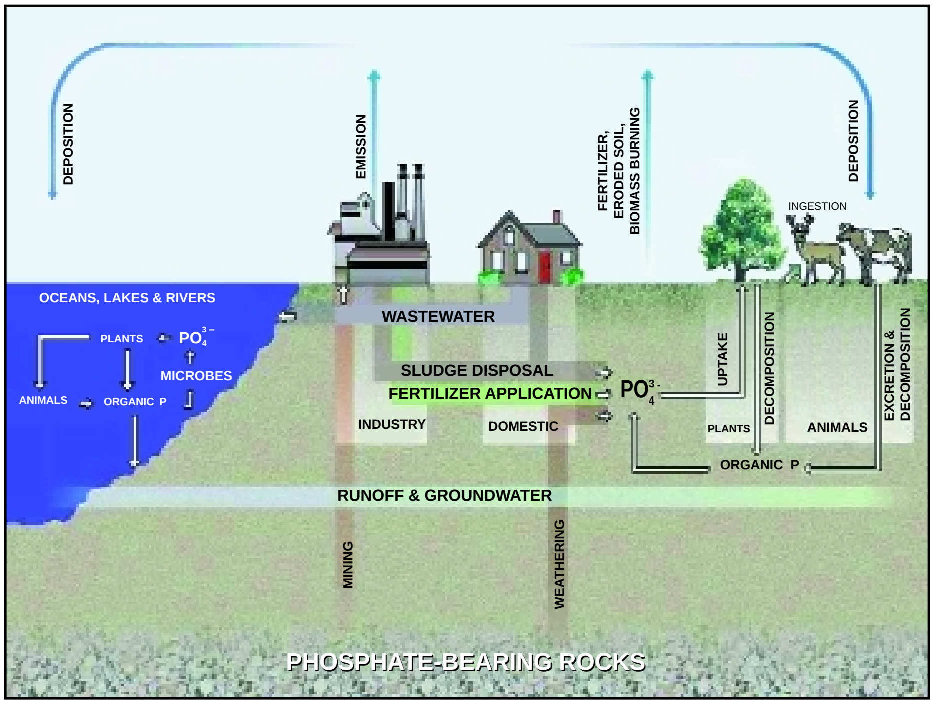
These activities have more than doubled the global rate of nitrogen fixation since pre-industrial times (Galloway et al. 1995; Vitousek et al. 1997a).

The importance of various components of the soil–plant pathway of the nitrogen cycle has also changed from pre-industrial to present times. In the pre-industrial world, the breakdown of soil organic matter by soil microorganisms supplied most of the nitrogen for plant growth. Now, however, fertilizers are a significant source of nitrogen for agricultural crops and, in some cases, for managed forests. The drainage of wetlands and the consequent oxidation of their organic soils have also liberated long-term biological storage pools of nitrogen. Municipal and industrial wastewater discharges and runoff from cities, farms, and forests have also redistributed nitrogen between terrestrial and aquatic environments and between ecosystems. Because the growth of most terrestrial vegetation is constrained by a shortage of nitrogen, the additional nitrogen supply, along with its redistribution, has likely increased plant growth and thus the quantity of organic carbon stored in terrestrial ecosystems (Vitousek et al. 1997a).

Phosphorus exists naturally only in compounds and not in its elemental state. The largest reservoir of phosphorus is phosphate-bearing rock, such as apatite. In the atmosphere, phosphorus is derived from such sources as soil and rock erosion, fertilizer drift, and industrial emissions. Phosphorus exists in only one environmentally reactive form, orthophosphate ($PO_4^{3-}$).

Prior to urbanization, industrialization, and intensive agriculture, phosphorus was added to soil only through the weathering of rocks (Figure 2). Phosphorus is taken up from the soil mainly as orthophosphate compounds through plant root systems or other cells and passed up the food chain by grazing animals to carnivores. When animals excrete excess phosphorus as phosphorus salts in urine, the phosphorus is either taken up directly by organisms or converted from organic phosphorus back to the orthophosphate form by phosphatizing bacteria (Ricklefs 1990). The decomposition of organic matter also returns phosphorus to the soil. Phosphate is extremely reactive and binds with iron, calcium, and many other elements to form relatively insoluble compounds. This binding results in the removal and storage of phosphate from both terrestrial and aquatic ecosystems.

**Figure 2: The phosphorus cycle**



Source: Chambers et al. (2001), Figure 2.3.

At present, however, the use of fertilizer produced from phosphorus-bearing rock has altered the natural pattern of phosphorus addition to soils. These fertilizers are applied in locations where the soil is naturally lower in phosphorus and at rates that far exceed natural weathering. Phosphorus is also contributed to water by municipal and industrial wastewater discharges, to the air by smokestack emissions, and to soils by landfills and the use of sewage sludge as fertilizer. Runoff from cities, farms, and managed forests is also a major phosphorus source for vegetation. The result is that the amount of biologically reactive phosphorus is able to increase. The consequences of this are particularly significant for freshwater ecosystems, because plant growth in these ecosystems is often limited by the availability of phosphorus.

# 2

# Enrichment Effects of Nutrient Additions

Nutrient addition promotes plant growth in all ecosystems, except those few that are already nutrient rich. In aquatic ecosystems, an increase in the supply of nutrients to nutrient-limited systems will increase plant production and may lead to eutrophication. Whereas the supply of phosphorus is the factor that typically limits plant production in fresh waters, the supply of nitrogen is generally the determining factor in ocean waters (Howarth 1988; Vollenweider 1992). For much of the Earth's surface, particularly in temperate and boreal regions, terrestrial plant production is also limited by nitrogen supply (Vitousek and Howarth 1991).

This section examines the processes through which nutrient additions affect ecosystems and the consequences that result. A summary of the effects of excess nutrients on aquatic ecosystems is provided in Table 1.

## Lakes

Nutrients promote the growth of phytoplankton, mostly microscopic algae that are the food source for zooplankton, which, in turn, are eaten by fish and other organisms higher in the food web. In lakes, algal growth is often limited by the amount of phosphorus available in the water. The relative abundance of algae is a good indicator of the nutrient content or "trophic" status of a lake. *Oligotrophic* lakes have very low nutrient concentrations, and algae are therefore low in abundance and the water is clear. Moderately productive lakes are said to be *mesotrophic*, whereas *eutrophic* lakes are very rich in nutrients and the water is green with algae most of the summer. At very high nutrient concentrations, there may be so much algae in the water that light becomes a limiting factor for additional algal growth. Lakes with extremely high nutrient concentrations and enormous algal growth are termed *hypereutrophic*.

Lakes have a capacity to absorb nutrients; when this capacity is exceeded, nutrient concentrations rise and eutrophic conditions may develop, accompanied by such effects as obnoxious growths of algae. One way that nutrient problems in lakes may occur is when nutrients are loaded in nearshore areas, via municipal wastewater outfalls and rivers, where dilution by the movement and mixing of water is minimal. Because effluents may have 10–100 times the phosphorus concentration desired in the ambient water, dilution is critical to reducing pollution effects.

**Table 1: Summary of the effects of excess nutrients on aquatic ecosystems**

| Ecosystem type | Potential enrichment effects on: | | | |
|---|---|---|---|---|
| | **Water quality and characteristics** | **Plants** | **Animals** | **Human health and economy** |
| **Lakes** | | | | |
| Moderate enrichment | | • increased phytoplankton and rooted aquatic plants<br>• changes in aquatic plant species composition | • increases in the abundance and changes in the composition of aquatic animals (invertebrates and fish) | |
| Gross enrichment | • obnoxious growths of nuisance algae (e.g., *Cladophora*)<br>• degradation of visible water quality (increased turbidity, green colouring)<br>• depletion of oxygen by decaying organic matter in sewage, industrial, aquacultural, and agricultural inputs and, in bottom waters, by decaying algae | | • smothered lake bottoms, resulting in reduced biodiversity of benthic organisms<br>• reduced survival of fish eggs due to oxygen depletion | • degraded shorelines and reduced recreational use due to nuisance algae<br>• increased costs for drinking water filtration and taste and odour problems<br>• poisoning of livestock and people by toxins produced by blue-green algae<br>• reduced aesthetics and recreational use<br>• cleanup and remediation costs of overfertilized waters (e.g., aquatic plant harvesting equipment, building of effluent diversions, removal of phosphorus from the waters, dredging, etc.) — applies to all aquatic ecosystem types<br>• economic losses due to fish kills and increased need to import fish — applies to all aquatic ecosystem types |

*(continued on next page)*

**Table 1: Summary of the effects of excess nutrients on aquatic ecosystems**

| Ecosystem type | Potential enrichment effects on: | | | |
|---|---|---|---|---|
| | **Water quality and characteristics** | **Plants** | **Animals** | **Human health and economy** |
| **Rivers and streams** | | | | |
| Moderate enrichment | • downstream transport of nutrients | • increased periphyton biomass and/or rooted aquatic plants | • increases in productivity for higher trophic levels (e.g., insects and fish) | |
| Gross enrichment | • deoxygenation of the water | • reduced productivity by periphyton | • reduced productivity by benthic invertebrates and fish and loss of species | • reduced aesthetics and recreational use<br>• impediments to boat passage (caused by rooted aquatic plants)<br>• blockage of water intakes by rooted aquatic plants |
| **Wetlands**<br>Freshwater wetlands | • water balance changes due to increased evapotranspiration rates | • increase in emergent biomass<br>• decrease in plant species diversity due to competition for light (shoot) and space (root)<br>• number of rare species decreases<br>• invasion by aggressive, nitrogen-loving, highly tolerant, non-native plants (e.g., purple loosestrife, water hyacinth, and salvinia), or dominance by a monoculture of cattails or common reeds<br>• direction of wetland succession altered by changes in vegetative biomass and species composition<br>• *bogs*: decline in *Sphagnum* abundance and replacement with more nitrogen-loving mosses<br>• *fens*: increases in tall graminoids (grasses, sedges) and decreases in subordinate plant species less able to compete for light | • nitrate and nitrite toxicity to amphibians (frogs, toads, salamanders)<br>• changes in invertebrate species composition<br>• changes in waterfowl food (quality and quantity) | |

*(continued on next page)*

**Table 1: Summary of the effects of excess nutrients on aquatic ecosystems**

| **Ecosystem type** | **Potential enrichment effects on:** | | | |
|---|---|---|---|---|
| | **Water quality and characteristics** | **Plants** | **Animals** | **Human health and economy** |
| Freshwater wetlands *(cont'd)* | | • *marshes*: increased phytoplankton and emergent vegetation | | |
| Saltwater wetlands (salt marshes) | | • waters can be choked with phytoplankton, blocking light penetration to deeper vegetation | • large amounts of nutrients released from salt marshes to adjacent estuaries, stimulating coastal water food webs | |
| **Coastal waters** | • increased microbial activity due to sedimentation of organic matter causes oxygen demand to exceed oxygen production, resulting in deep-water anoxia<br>• overenrichment creates niche occupied by dinoflagellates and diatoms that produce toxic chemicals | • increases in fast-growing phytoplankton and macro-algae, and reduced light to seagrasses, diminishing their ability to photosynthesize<br>• sediment anoxia impairs the ability of seagrasses to acquire nitrogen and accelerates seagrass mortality<br>• turbidity increases as sediments are no longer stabilized, further favouring motile phytoplankton that can move to the surface to maximize exposure to light<br>• anoxia also enhances release of nutrients from the sediments (internal nutrient loading), favouring phytoplankton | • loss of habitat for many fish and benthic organisms<br>• marine algae have been found responsible for massive mortalities of fish, birds, and marine mammals | • eutrophication of coastal wetlands decreases or alters breeding habitats for commercially important fish species<br>• marine algae responsible for at least four different illnesses in human consumers of molluscs<br>• large economic impacts on coastal communities as a result of closures of shellfish fisheries<br>• increased anoxia in deep water decreases fish egg survival and decreases the area of available habitat for reproduction |
| **Groundwater** | • indirect effect: groundwaters are connected to lakes, rivers and streams, wetlands, and coastal waters, and therefore are a source of nutrients to them | | | • nitrate, ammonia, and other nutrient contamination of waters for human consumption<br>• livestock deaths due to nitrate contamination from groundwater irrigation sources |

Although algae are the foundation on which the rest of the aquatic food chain ultimately depends, excessive algal production tends to reduce the diversity of populations in a lake and simplify its food web. The survival of species such as trout or bass becomes more tenuous, and so-called "coarse" fish species, such as carp, may come to dominate the fish population.

There are a number of reasons why an explosion of algal productivity should adversely affect many species, but the most important involve depletion of the lake's oxygen supply and the accumulation of organic debris. Plankton go through boom and bust cycles; when populations die off, their decomposition draws large amounts of dissolved oxygen from the water, causing stress to fish and invertebrates. Large quantities of plants can also affect the oxygen supply on a daily basis. Aquatic plants produce oxygen during the daytime through photosynthesis; at night, however, when photosynthesis has ceased, they consume oxygen, so that dissolved oxygen levels fall very low where plants are abundant. In addition, the overabundance of organic matter caused by excessive algal populations can smother the lake bottom and reduce the diversity of bottom-dwelling organisms. Organic matter also accumulates in crevices between rocks where decay can consume enough oxygen to impair the survival of fish eggs. As organic matter accumulates in sediments, nuisance accumulations of aquatic rooted plants are more likely to occur.

Deoxygenation is most severe in the cold, bottom waters of eutrophic lakes. In early summer, solar radiation warms the surface waters of lakes in temperate climates, resulting in the formation of warm and cold layers. Because the solar radiation is rapidly absorbed in the upper portion of the lake, the deeper waters remain cold. This cold bottom layer, known as the *hypolimnion*, is denser than the overlying warm water and thus does not mix easily with it. As a result, when oxygen is consumed in the hypolimnion, it cannot be replaced by diffusion from the warmer water above it. When bacteria feed on the abundance of organic matter that falls to the bottom of eutrophic lakes, they can rapidly use up the hypolimnion's limited and finite oxygen supply.

If the oxygen concentration in a lake's hypolimnion gets too low, organisms may die or be forced out of the hypolimnion. Under less severe circumstances, persistently low oxygen concentrations can cause coldwater species that require high concentrations of dissolved oxygen (e.g., trout and sculpins) to be replaced by warmwater species (e.g., walleye, pike, and smallmouth bass) with lower oxygen requirements.

A partial or complete lack of oxygen in the hypolimnion can add to a lake's nutrient loadings by causing phosphorus to be released from the bottom sediments. The phosphorus then diffuses upward into the surface water and stimulates further algal production. In shallow lakes, decades of pollution can cause the release of phosphorus from bottom sediments even under oxygenated conditions. The release of phosphorus from sediments can slow the recovery of a lake after external loadings have been reduced.

## Rivers

Responses to nutrient addition can differ markedly between running and standing water systems, primarily because of differences in the flow of nutrients in them and the species that inhabit them (Welch 1992). For example, downstream transport is a major factor in the transfer of nutrients in rivers, whereas the most important exchanges in lakes occur between sediments and deep water and between deep water and shallow water. In addition, the primary producers that absorb nutrients at the bottom of the food chain in small rivers and streams are algae attached to rock surfaces (*periphyton*) and, in large rivers, phytoplankton, as in lakes.

The effects of nutrient additions on rivers depend on a number of factors. In rivers where plant growth is limited by a shortage of nutrients, inputs of phosphorus and nitrogen will be carried only a short distance before being taken up by the rivers' plants. In rivers where factors other than nutrients determine plant abundance, new inputs of nitrogen and phosphorus will be carried downstream with only minor losses. As in lakes, large loadings of nutrients over time are likely to deoxygenate the water. When that happens, the river becomes less productive at all levels of the food web, and species are lost. Small or moderate additions of nutrients, however, may actually make rivers with low nutrient concentrations more productive, without any loss of species. For example, fertilizer addition to the Keogh River in British Columbia resulted in a 5- to 10-fold increase in periphyton biomass, and salmonid fry weights increased by a factor of 1.4–2 (Johnston et al. 1990).

Besides the amount of nutrients added, the duration of nutrient loadings is also important. Nutrient additions that are limited to a short duration (e.g., a wastewater spill) and are diluted to non-toxic concentrations often have little effect on an ecosystem. In contrast, additions over an extended period (e.g., a continuous effluent discharge for months or years) can cause habitat alteration and changes in the abundance and composition of the river's plants and animals.

Because nutrient inputs to rivers are responsible for increased plant growth, removal or reduction of these inputs should improve conditions in heavily polluted rivers. In British Columbia's Thompson River, for example, the start-up of a bleached kraft mill at Kamloops in 1972 was associated with massive accumulations of periphyton algae. Changes to the operation of the municipal sewage treatment system in Kamloops and the mill's wastewater treatment system reduced total phosphorus loadings by about 35% between 1973 and 1989. This decline coincided with a 60% decline in periphyton biomass (Bothwell et al. 1992). Similarly, improvements to Calgary's municipal wastewater treatment plant reduced total phosphorus, ammonia, and nitrate plus nitrite loadings to the Bow River by 80%, 53%, and 50%, respectively, between 1982 and 1988. This reduction coincided with a considerable decline in the biomass of rooted aquatic plants (A. Sosiak, Alberta Environmental Protection, Calgary, unpublished data).

## Wetlands

The addition of nutrients to wetlands generally leads to two consequences: an increase in emergent biomass (Wisheu et al. 1991) and a decrease in plant species (Wilson and Keddy 1988). Moreover, as the nutrient supply increases, the number of rare plants in wetland communities decreases (Moore et al. 1989). Vegetation surveys and controlled laboratory fertilization experiments have shown that increases in the availability of nitrogen and phosphorus at first result in increases in the number of species and in biomass production. After a certain threshold, however, the number of species decreases as a result of competition for light and space (e.g., Al-Mufti et al. 1977), with only a few dominant species surviving. Nitrogen addition can result in invasion by aggressive nitrogen-loving, non-native vegetation, such as purple loosestrife, water hyacinth, and salvinia, or dominance by a monoculture of cattails or common reeds (Mitsch and Gosselink 1993).

As freshwater and saltwater wetlands differ on the basis of their vegetation, water supply, and chemistry, the effects of nutrient addition on them are considered separately.

Bogs are typically acidic wetlands that derive their nutrients from the atmosphere and are therefore particularly sensitive to airborne nitrogen loadings (Urban and Eisenreich 1988). There are no reports on the effects of nitrogen enrichment on bogs in Canada; however, studies in Scotland, the Netherlands, and Denmark have shown that the dominant vegetation, varieties of *Sphagnum* and other plant species that favour low nitrogen concentrations, may decrease in abundance and be replaced by plants with a greater preference for nitrogen (Lee et al. 1989; Greven 1992; Aaby 1994). The nitrogen-favouring species, such as cottongrass, may also contribute to the decline of the original vegetation by being more effective at competing for light and other necessities (e.g., see World Health Organization 1997).

In contrast to bogs, fens are typically alkaline or only slightly acidic (National Wetlands Working Group 1988). Studies of mesotrophic fens in the Netherlands have shown an increase in the diversity of tall graminoids (e.g., grasses or sedges) and a decrease in shorter plant species in response to nitrogen addition (Verhoeven and Schmitz 1991; Koerselman and Verhoeven 1992).

Marshes, both freshwater and saltwater, remove pollutants from water passing through them. For that reason, thought has sometimes been given to using them for secondary treatment of urban and industrial wastewater. However, the large quantities of organic matter in these wastes can reduce dissolved oxygen concentrations in the marsh waters; the nutrients in urban waste can also cause the marsh to become choked with phytoplankton, which can prevent light from penetrating to deeper vegetation (MacKinnon and Scott 1984). Marshes are, nonetheless, suited for nutrient removal in tertiary wastewater treatment (MacKinnon and Scott 1984; Kadlec and Knight 1996) and in stormwater treatment. However, when the loadings are too great or the filtering capacity of these wetlands is exceeded, the marshes begin to die.

## Coastal waters

Coastal waters, including fjords, estuaries, lagoons, and continental shelves, comprise only 1–2% of the total area of the ocean, yet they are responsible for 20% of global primary production — that is, the production of plants (Duarte 1995). As noted above, the supply of nitrogen is generally the determining factor in ocean waters. Since the early 1980s, eutrophication of coastal waters as a result of human activities has been increasingly recognized as a global problem (United Nations Environment Programme 1995; Paerl 1997). In the case of nitrogen, most inputs to coastal waters come from non-point sources such as agriculture (National Research Council 1993). For the entire coastline of the North Atlantic Ocean, non-point sources of nitrogen are approximately nine-fold greater than inputs from wastewater treatment plants (Howarth et al. 1996). Non-point inputs of phosphorus are also significant, although point sources, such as sewage treatment plants, may be large contributors in many environments (Carpenter et al. 1998). On a more local scale, the expansion of the aquaculture industry has raised concerns about its contribution to eutrophication, especially in the areas immediately under fish cages (see the “Aquaculture” section under “Sources of Nutrient Additions”).

The nature and extent of eutrophication in coastal waters are largely determined by the exchange of water with the open ocean. This is accomplished by currents and tidal patterns that mix nutrient-poor water from the open ocean with the nutrient-rich water of the coastal zone, thus diluting the nutrient concentrations of the coastal waters. In areas where light is plentiful and the availability of nutrients limits aquatic plant production, the process of eutrophication results in the displacement of slow-growing seagrasses and large macroalgae by other faster-growing macroalgal species and phytoplankton. Because the latter species inhabit the surface layer of the water, they diminish the amount of sunlight reaching the seagrasses below them.

The survival of the seagrasses is further threatened as organic material from decaying phytoplankton accumulates on the seafloor and provides food for microbes that deplete the sediments of oxygen. Without oxygen, the seagrasses have difficulty acquiring nitrogen and die. With the loss of seagrasses, the sediment is no longer stabilized, and the water becomes more turbid. This situation further favours the survival and reproduction of motile phytoplankton that can move to the surface to maximize light exposure (Duarte 1995). This change in the structure of the marine plant community is thus a self-accelerating cascade caused by the direct and indirect effects of increased nutrient loadings and increased shading of plants that live on the sea bottom. The result is a shift from an environment limited by the availability of nutrients to one limited by the availability of light.

The loss of seagrasses in coastal zones means a loss of habitat for many fish and bottom-dwelling organisms. In deep water, lack of oxygen also decreases both fish egg survival and the area of habitat available for reproduction. This habitat loss ultimately results in a notable shift from a fish community dominated by the larger, bottom-dwelling fish species to one composed primarily of smaller, open-water fish species (Kerr and Ryder 1992).

## Forests

Nitrogen is considered to be the nutrient that most often limits net primary production in forests, particularly those in temperate and boreal regions (e.g., Vitousek and Howarth 1991). For trees, fertilization studies have confirmed that nitrogen is the major growth-limiting element in many Canadian forests (e.g., Weetman et al. 1987). Human activities have greatly increased airborne emissions of nitrogen, which, in turn, have led to enhanced deposition of biologically available nitrogen on the Earth's surface. A large portion of this extra nitrogen is retained in forests and stimulates production (for discussion, see Vitousek et al. 1997a). In Canada, atmospheric deposition of nitrogen in the form of ammonium and nitrate has steadily increased since the 1900s and, in the 1990s, was estimated to supply, on average, 2.5 kilograms of nitrogen per hectare per year to forests (Chambers et al. 2001). This value is five times the pre-industrial value of 0.5 kilograms of nitrogen per hectare per year.

Excess nitrogen can be converted to nitrate, which may then be leached to surface water or groundwater. Nitrate leaching has been found to cause changes in soil chemistry, in particular a loss of nutrient cations such as calcium and magnesium, an increase in soil acidity, and an increase in the availability of aluminum (due to the increased acidity). Leaching of nitrate and associated cations can, in turn, cause nutrient imbalances in trees, in particular changes in the ratios of calcium to aluminum and magnesium to nitrogen. These imbalances have been linked to reductions in net photosynthesis, tree growth, and tree mortality (e.g., Cronan and Grigal 1995), and they may also increase the likelihood of damage caused by weather extremes, particularly high temperatures in late winter, hard frosts in early spring, or prolonged drought.

## Socioeconomic effects

Algal growth and other consequences of eutrophication can also have a variety of impacts on recreational, municipal, and industrial water uses. The aesthetic enjoyment of the water may be impaired by turbidity, discoloration, foaming, and odour, while long strands of nuisance algae such as *Cladophora* can restrict swimming, foul fishing gear, damage boat motors, and impede navigation. In some cases, municipalities and industry may be faced with higher maintenance costs to clear clogged intake pipes, and communities may have to pay for additional filtration of drinking water to reduce taste and odour problems (Anderson and Quartermaine 1998).

## Regional overview of enrichment in Canada

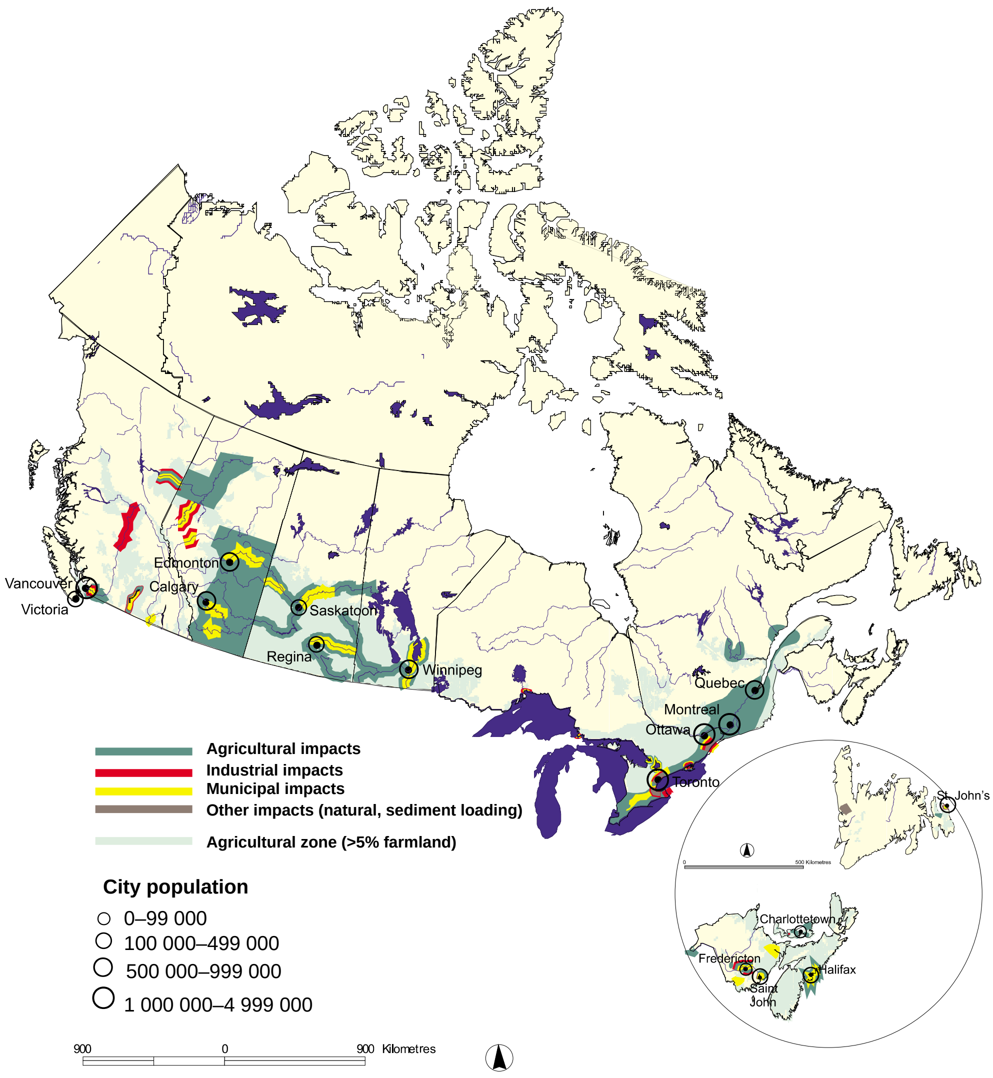
A review of water quality in Canada's lakes, rivers, and coastal waters indicates that the most serious eutrophication problems exist in the southern Prairie provinces and in southern Ontario and Quebec (Figure 3).

In the southern Prairie provinces, eutrophication is generally the single most important water quality issue (Government of Canada 1996; Hall et al. 1999) (see Box 1). Nitrogen and phosphorus concentrations in many watersheds tend to be naturally high, and agricultural activity in the area is intensive. As a result, rivers that rise in the Prairies often receive large inputs of nutrients from both natural and human sources. Lakes in the southern Prairie provinces also easily accumulate excessive concentrations of nutrients, as they tend to be small and shallow and many of the smaller water bodies dry up periodically. The large rivers that rise in the mountains, like the North and South Saskatchewan and the Bow, generally have much better water quality upstream of cities such as Edmonton, Calgary, and Saskatoon, but the water quality becomes poorer downstream of these and other urban areas and in areas of intensive agriculture, as in the case of Alberta's Oldman River (Government of Canada 1996).

In southern Ontario, nitrogen and phosphorus from agriculture, municipal sewage, and industrial wastewater have had a substantial impact on many water bodies (see Figure 3). The effects are especially apparent in the Lake Erie basin, where some of Canada's most intensive agricultural activity combines with growing urbanization. Other large Ontario lakes, such as Simcoe and Rice, have also experienced nutrient impacts. In addition, many southern Ontario rivers (e.g., the Thames, Grand, Don, and Humber) have total phosphorus concentrations that exceed Ontario's provincial water quality objective for rivers of 30 micrograms per litre and are thus considered eutrophic (D. Boyd, Ontario Ministry of the Environment, personal communication).

In southern Quebec, the effects of high nutrient inputs are apparent in rivers and lakes in the agricultural areas adjacent to the St. Lawrence lowlands. Between 1968 and 1988, most Quebec rivers surveyed had total phosphorus concentrations above the provincial guideline of 30 micrograms per litre, with agriculture being a major source (Painchaud 1997). Excessive nitrogen concentrations were also evident in some rivers. From 1979 to 1994, for example, 16% of the ammonium-nitrogen samples for the Yamaska River exceeded the guideline of 0.5 milligrams per litre.

### Figure 3: Documented sites of nutrient enrichment in Canada, 1998



Note: The sites of excess nutrients in Canada also reflect to a certain degree the extent of monitoring.

Source: Chambers et al. (2001), Figure 4.10.

Inland waters throughout Nova Scotia, New Brunswick (e.g., Saint John River and Black Brook), and Prince Edward Island (e.g., Boughten River) are affected by agriculture and industrial development and show varying degrees of eutrophication (Figure 3).

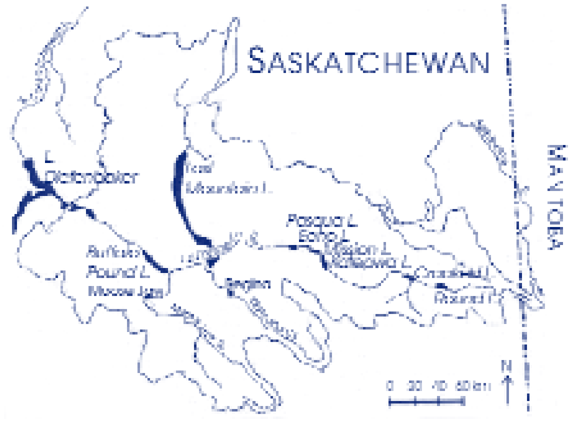
British Columbia has fewer eutrophication problems than most other provinces. The principal exception is the heavily populated lower Fraser River basin (Figure 3), where agricultural runoff and municipal effluents combine to cause enrichment. In fact, an estimated 90% of the province's municipal wastewater is discharged into the lower Fraser or its tributaries (Government of Canada 1996). There is little direct evidence of the enrichment of coastal marine waters, however, because of the high flushing rate in the open waters. Only poorly flushed bays show signs of eutrophication.

## Box 1: Eutrophication in the Qu'Appelle Valley drainage basin and lakes, Saskatchewan

The Qu'Appelle River in south-central Saskatchewan extends over 400 kilometres from its headwaters near Lake Diefenbaker in western Saskatchewan to its confluence with the Assiniboine River in western Manitoba (Figure 4). It and its tributaries provide water to approximately one-third of Saskatchewan's population, including the cities of Regina and Moose Jaw. Agricultural fields and pastures comprise more than 95% of land use in the 52 000-square-kilometre drainage basin (Hall et al. 1999). A chain of eight lakes, including two headwater reservoirs (Lake Diefenbaker and Buffalo Pound Lake), are used for commercial and game fishing, recreation, irrigation, livestock watering, drinking water supply, and sewage discharge, in addition to providing flood control and waterfowl habitat (Chambers 1989).

The natural lakes of the Qu'Appelle Valley are less than 35 metres deep, are hypereutrophic, and produce immense blooms of blue-green algae throughout the summer (Hall et al. 1999). Current water quality in the lakes is worse than it was before the beginning of European settlement and intensive agricultural development of the region (Hall et al. 1999). The current excessive algal and plant growth in the Qu'Appelle lakes has been attributed to high nutrient concentrations in municipal wastewater discharges and agricultural runoff.

**Figure 4: Qu'Appelle Valley drainage basin and lakes**



Source: Chambers et al. (2001), Figure 4.4.

The 1975 Qu'Appelle Agreement between the governments of Canada and Saskatchewan provided an impetus to deal with these problems and make the region more attractive for tourism and recreational activities (Chambers 1989). In 1976, Regina upgraded its municipal wastewater treatment plant to tertiary treatment to improve phosphorus removal, and by 1987, Moose Jaw had diverted all of its sewage to agricultural land through the use of spray irrigation (Chambers 1989).

Wastewater treatment has not had the desired effect on water quality in the Qu'Appelle lakes, however. Although open-water total phosphorus concentrations and influxes in the lakes have decreased, nitrogen loadings to the lakes reached an all-time high in the late 1990s (Hall et al. 1999). Analyses indicate that the algal biomass is currently three times greater than it was before European settlement began (Hall et al. 1999; Dixit et al. 2000). Various studies (e.g., Graham 1997) have also shown that primary production in the Qu'Appelle Valley is limited by inputs of nitrogen rather than phosphorus. Consequently, water quality in the valley is unlikely to improve until nitrogen loadings to the lakes are reduced.

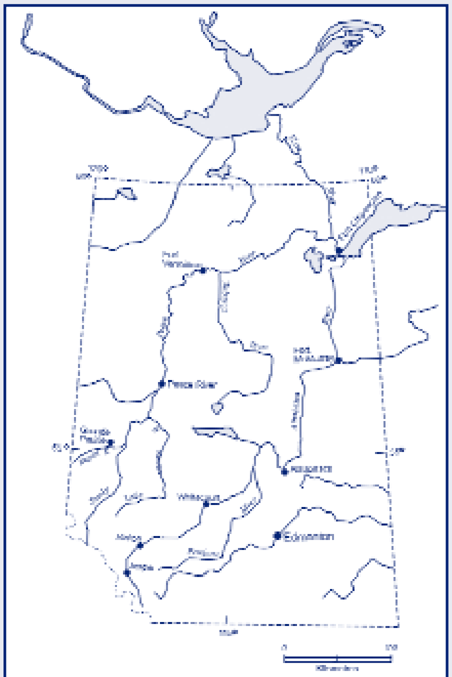
## Box 2: Impacts of pulp mills and municipal effluents on rivers in northern Alberta

Expansion of the forestry industry in the boreal forest of western Canada since the early 1980s has raised concerns about the effect of pulp mill effluents on nutrient concentrations in rivers and the resulting potential for eutrophication. Many pulp mills in western Canada have been designed or recently upgraded to eliminate or substantially reduce concentrations of toxic organic contaminants and oxygen-depleting substances in their effluent. Until recently, however, little consideration had been given to the presence of nutrients in pulp mill wastes.

The Northern River Basins Study, which ran from 1992 until 1996, examined conditions in several rivers in northern Alberta and the effects of development on them (Figure 5). One component of the study assessed the effects of pulp mill and municipal effluents on the nutrient status and potential for eutrophication of the Athabasca, Wapiti, Smoky, and Peace rivers, all of which rise in the mountains. Their basins are relatively sparsely populated and largely forested, although agricultural land comprises 17% of the Wapiti–Smoky river basin. The waters of the four rivers are normally nutrient poor.

These studies revealed elevated nitrogen and phosphorus concentrations in the Athabasca River downstream of Jasper, Hinton, Whitecourt, and Fort McMurray and on the Wapiti River downstream of Grande Prairie during fall, winter, and spring. Elevated nutrient concentrations in the Athabasca and Wapiti rivers increased the amount of periphyton algae growing on rocks and other surfaces and the abundance of bottom-dwelling invertebrates.

**Figure 5: The Athabasca, Wapiti, Smoky, and Peace rivers in northern Alberta**



Source: Chambers et al. (2001), Figure 4.6.

Evidence that pulp mills were contributing to eutrophication of the Athabasca and Wapiti–Smoky rivers resulted in public recommendations to the federal and Alberta governments to eliminate or substantially reduce nutrient discharges to northern rivers, cap direct nutrient loadings into specific reaches of the Athabasca and Wapiti–Smoky rivers, and reduce phosphorus in pulp mill effluents to minimal concentrations (Northern River Basins Study Board 1996). In the years since these recommendations were made, Alberta Environment has worked with kraft mill and municipal authorities to decrease nutrient loadings to the most affected rivers (the Wapiti–Smoky system in Alberta) and has stated that any future industrial developments in this basin will be subjected to stringent discharge requirements. In addition, the federal government has required all pulp mills to undertake an environmental effects monitoring program that includes an assessment of changes in trophic status as a result of effluent inputs.

In the boreal forest zone that stretches across Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Newfoundland, problems of excessive nutrients are uncommon. Where they do occur, they are typically associated with specific human-related sources (Figure 3). Zones of enrichment, for example, have been found downstream of municipal or industrial outfalls on the Athabasca and Wapiti rivers of northern Alberta (Chambers 1996; Wrona et al. 1996) (see Box 2).

Phosphorus concentrations also increased in Ontario's Haliburton and Muskoka districts as a result of rapid cottage development during the 1980s. This was largely caused by increased runoff due to land clearing and construction; with the end of the construction boom and the landscaping of the cottage lots, however, total phosphorus values have decreased to pre-development values (A. Gemza, Ontario Ministry of the Environment, personal communication). In 1997, only 20 out of 318 Ontario cottage lakes sampled by the Lakes Partner Program had bays or inlets with total phosphorus values greater than 21 micrograms per litre, the nutrient guideline that would designate them as eutrophic (Ontario Ministry of the Environment 1998).

# 3

# Toxic Effects of Nutrient Additions

Although naturally occurring phosphorus compounds do not present any significant toxic risks, certain nitrogen compounds can cause adverse health effects for plants and animals, including humans. This chapter describes the toxic effects of nitrogen compounds on various organisms and then evaluates the extent to which toxic concentrations of nitrogen occur in Canada and their associated impacts on biota.

## Direct toxic effects of nitrogen

### Aquatic plants and animals

Ammonia in water can be toxic at elevated concentrations. The few studies that have been carried out on the toxicity of ammonia to freshwater vegetation have shown that concentrations greater than 2.4 milligrams of total ammonia (i.e., ammonia plus ammonium) per litre inhibit photosynthesis and growth in algae (e.g., World Health Organization 1986). In experiments with rooted aquatic plants, ammonia reduced the length and weight of roots and shoots (Stanley 1974; Litav and Lehrer 1978). There have been no conclusive toxicity tests on saltwater plants.

In most surface waters, total ammonia concentrations greater than about 2 milligrams per litre are toxic to aquatic animals (Mueller and Helsel 1996), although this varies among species and life stages. Sublethal exposure to ammonia has been reported to cause adverse physiological effects and tissue damage in fish (National Research Council 1979). Little information is available on the toxic effects of ammonia on aquatic invertebrates.

Although nitrates in water are relatively non-toxic, nitrate concentrations in the range of 1–10 milligrams per litre have been shown to be lethal to eggs and, to a lesser extent, fry of salmon and trout species (Kincheloe et al. 1979). Exposure of tadpoles from various amphibian species to nitrate has led to behavioural changes, reduced survivorship, and other effects at concentrations as low as 11 milligrams of nitrate per litre (Hecnar 1995). Furthermore, tadpoles exposed to 11–44 milligrams of nitrate per litre for 24 hours showed developmental abnormalities, reduced feeding activity, and weight loss, swam less vigorously, and displayed disequilibrium and eventually paralysis (Hecnar 1995).

Under some conditions, nitrate and ammonia can be transformed to highly toxic nitrite (Marco and Blaustein 1999). It is suspected that nitrite can reach lethal levels in sewage plant receiving waters, as well as in aquaculture systems and in ponds and other natural systems where animal biomass is high (Huey and Beitinger 1980a). However, it rapidly oxidizes to nitrate and is therefore rarely present in high concentrations naturally. In recent studies of cascades frogs (*Rana cascadae)*, nitrite concentrations of 3.5 milligrams per litre induced behavioural and morphological changes, retarded development, and altered the age at emergence from tadpole to frog (Marco and Blaustein 1999). Nitrites also decrease the oxygen-carrying capacity of the blood by transforming hemoglobin, which transports oxygen, into methemoglobin, which does not. Nitrite concentrations as low as 1 milligram per litre have been shown to increase the amount of methemoglobin in the blood of bullfrog tadpoles (Huey and Beitinger 1980b). Occupying shallow waters, bobbing, air gulping, and other behavioural modifications have been noticed in amphibians in response to nitrite concentrations of 3.5–10 milligrams per litre in surface waters (Huey and Beitinger 1980b; Marco and Blaustein 1999).

## Terrestrial plants and animals

Air pollution exposes plants to various forms of nitrogen, including nitrogen dioxide, ammonia, and ammonium, all of which can be highly toxic to plants. Symptoms of toxicity as a result of exposure to these compounds include leaf loss, formation of larger, thin-walled cells, needle yellowing and lesions, and reductions in the ability to withstand drought and frost (Chambers et al. 2001). In the case of nitrogen dioxide, the greatest direct effect on vegetation lies in its interaction with other pollutants to form ground-level ozone (smog) and in disrupting balances with other nutrients (World Health Organization 1997).

Ammonium toxicity in plant tissues is known to occur at quite low concentrations and is generally characterized by an immediate reduction in growth rate, wilting, death of tissues along leaf margins, discoloration of terminal leaves, and, ultimately, the death of the entire plant (Maynard and Barker 1969). Atmospheric ammonium ions may also have contributed to recent episodes of forest decline by affecting frost hardiness; changes in frost hardiness of only a few degrees could significantly increase the risk of frost damage (Hall et al. 1997).

Leaf uptake of ammonia is also possible. The toxic effects of high ambient concentrations of ammonia are most often seen in older leaves or needles and include discoloration and spotting, followed by blackening and drying up of the entire leaf. On broad-leaved woody plants exposed to high concentrations of ammonia, injury symptoms usually begin as large, dark-green, water-soaked areas that darken after several hours to brownish-grey or black lesions that are widely scattered over the leaf surface (National Research Council 1979). Conifer needles exposed to ammonia darken to shades of grey-brown, purple, or black (Dueck et al. 1990). Symptoms of injury are more variable on herbaceous plants than on woody species (Hall et al. 1997; World Health Organization 1997). As with ammonium, ammonia exposure can increase sensitivity of plants to cold and frost; thus, elevated atmospheric ammonia concentrations may also lead to forest decline.

Terrestrial animals receive toxic concentrations of nitrogen compounds primarily through the consumption of vegetation with high nitrate levels or through air pollution (nitrogen dioxide, ammonia, or nitrate). Nitrates can accumulate to high levels in certain plant species, in particular common plants that are used for livestock feed. Toxicity begins to occur when the proportion of nitrate in livestock feeds exceeds 0.65% of the dry weight of the feed (Stoltenow and Lardy 1998). The frequent use of nitrogen fertilizers in recent years has resulted in an increased incidence of nitrate poisoning (Kvasnicka and Krysl 1996).

Nitrate in vegetation is not toxic to livestock until it is converted to nitrite in the animal's digestive tract. Nitrite is absorbed into the blood and converts hemoglobin to methemoglobin, thus decreasing the oxygen-carrying capacity of the blood (Yaremcio 1991). Cattle and sheep are more susceptible to poisoning, because microorganisms in their rumen (their first stomach) favour this conversion to nitrite (Osweiler et al. 1985). Horses and pigs are less susceptible, because they convert nitrate to nitrite in the intestine, where there is less opportunity for nitrites to be absorbed by the blood (Yaremcio 1991). Nitrate or nitrite ingested in drinking water can also cause problems for livestock.

Signs of acute nitrate poisoning in livestock include rapid pulse (greater than 150 per minute) and respiration, muscle tremors, vomiting, weakness, blindness, excess saliva and tear production, laboured, noisy, or violent breathing, dark "chocolate-coloured" blood, staggered gait, low body temperature, disorientation, and an inability to get up (e.g., Yaremcio 1991; El-Bahri et al. 1997; Stoltenow and Lardy 1998). Sublethal responses include lower milk production, reduction in weight gain, lower resistance to disease, and a general lack of health (e.g., El-Bahri et al. 1997). Sublethal doses of nitrate also increase the incidence of stillborn calves, abortions, retained placentas, and cystic ovaries (e.g., Putnam 1989).

## Nitrogen concentrations and impacts in Canadian ecosystems

### Aquatic ecosystems

Ammonia is not routinely found in Canadian surface waters at high enough concentrations to pose a wide-scale toxic threat to invertebrates or fish. Elevated ammonia concentrations are usually associated with mixing zones near municipal and industrial wastewater discharges or with manure or fertilizer runoff from agricultural fields. These high ammonia concentrations are usually dissipated within tens or hundreds of metres from the source because of dilution in the receiving water, conversion of ammonia to nitrate by nitrification, and evaporation of ammonia to the atmosphere. Nevertheless, fish kills related to the discharge of nitrogen-containing material still occur.

Between 1987 and 1997, 353 fish kills were reported to Environment Canada's National Environmental Emergencies Centre. Of these, 22 were caused by discharges of nutrient-containing materials, and almost all of these contained nitrogen compounds (Table 2). Most of the reported fish kills were associated with agricultural activities, particularly the release of manure through storm or flood runoff, underground tank leaks, overflowing of storage facilities, or spraying of fields. All but one of the fish kills associated with the manufacturing and food processing industries were due to the routine discharge of ammonium or ammonia. Fish kills caused by municipal wastewater discharge were largely due to equipment failure, discharges from combined sewers, or the bypassing of wastewater treatment during storms. A more thorough examination of fish kills caused by agricultural activity in southwestern Ontario documented 42 fish kills for a similar time period (1988–1998) and showed that most agriculture-related fish kills are caused by spray irrigation of liquid manure from swine operations (Table 3).

**Table 2: Fish kills caused by the discharge of nutrient-related material from 1987 to 1997 as reported to the National Environmental Emergencies Centre, Environment Canada, Ottawa**

| Sector | Material | Number of incidents | Province |
|---|---|---|---|
| Agriculture | manure | 9 | Ontario, Manitoba |
| | nitrogen fertilizer | 1 | Ontario |
| Chemical manufacture | anhydrous ammonia/ ammonium chloride | 2 | Ontario |
| Food processing | ammonia | 2 | British Columbia, Nova Scotia |
| | manure | 1 | Ontario |
| General manufacturing | concentrated shampoo | 1 | Ontario |
| Municipal waste | sewage | 6 | New Brunswick, British Columbia, Ontario |

Note: Where there has been no finding of fact by a court, the incidents set out in this table are alleged only.

Source: Chambers et al. (2001), Table 5.7.

**Table 3: Manure spills and fish kills for southwestern Ontario, 1988–1998**

| Year | Number of spills | Fish kills | Route to stream | | How spill occurred | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Field tile | Overland runoff | Storage related | Irrigation applied | Tanker applied | Equipment failure | Transport related |
| 1988 | 23 | 6 | 21 | 2 | 1 | 21 | 2 | 2 | 2 |
| 1989 | 19 | 2 | 8 | 4 | 3 | 6 | 1 | 6 | 1 |
| 1990 | 29 | 2 | 22 | 5 | 3 | 15 | 5 | 3 | 2 |
| 1991 | 21 | 1 | 12 | 4 | 2 | 10 | 3 | 5 | 2 |
| 1992 | 22 | 4 | 11 | 6 | 1 | 11 | 2 | 3 | 2 |
| 1993 | 14 | 3 | 9 | 3 | 4 | 4 | – | – | – |
| 1994 | 15 | 2 | 9 | 3 | 3 | 2 | 3 | 4 | 2 |
| 1995 | 15 | 6 | 5 | 3 | 3 | 2 | – | 3 | 2 |
| 1996 | 20 | 4 | 7 | 2 | – | 3 | 2 | 4 | 3 |
| 1997 | 23 | 7 | 14 | 12 | 10 | 7 | 4 | – | – |
| 1998 | 13 | 5 | 9 | 4 | 4 | 6 | 2 | 1 | 1 |
| **Total** | **214** | **42** | **127** | **48** | **34** | **87** | **24** | **31** | **17** |

Source: Chambers et al. (2001), Table 5.8.

Although nitrate can be found in relatively high concentrations in surface waters, it is fairly non-toxic to aquatic plants, bottom-dwelling invertebrates, and fish (Russo 1985; see also Chambers et al. 2001, Table 5.2). Nitrate is, however, believed to be at least partly to blame for declines in amphibian populations in Canada (see Box 3). Lethal concentrations of nitrate for a number of amphibian species range from 13 to 40 milligrams per litre, with chronic effects occurring at concentrations as low as 2.5 milligrams per litre (Baker and Waights 1993, 1994; Hecnar 1995; Watt and Oldham 1995).

### Box 3: Are nitrates hampering the development and survival of amphibians?

Populations of amphibians around the world have been declining significantly. In Canada, substantial decreases have been observed in 17 of the country's 24 frog and toad species and 21 salamander species (Jacobs 1999). Acid precipitation, stratospheric ozone depletion and increased ultraviolet radiation, climate change, and the introduction of exotic species have all been offered as possible causes (Wyman 1990; Blaustein et al. 1994).

In agricultural landscapes, another possible explanation for declining amphibian numbers may be the death of their larvae as a result of exposure to excessive levels of chemical pollutants, including nitrates (e.g., Hecnar 1995; Marco and Blaustein 1999). Permeable skin and a dependence on aquatic habitats for reproduction, forage, larval development, and hibernation also contribute to the susceptibility of amphibians to water pollution (Vitt et al. 1990). The role of amphibians as important prey and predators and their major contribution to animal biomass in many food webs mean that factors affecting amphibian numbers can have far-ranging effects on ecosystems (Hecnar 1995; Hecnar and M'Closkey 1996).

Nitrogen-based fertilizers and animal wastes are the primary sources of nitrogen contamination of water in agricultural areas. Elevated concentrations of nitrate from these sources can have both acute and chronic toxic effects on amphibians (Berger 1989; Baker and Waights 1993, 1994; Hecnar 1995). One of the most common effects is poor growth during the larval stage, which can result in failure to escape from a deteriorating aquatic environment (Smith 1987), increased vulnerability to predation and desiccation (Watt and Oldham 1995), and reduced body size at maturity (Smith 1987), a factor associated with low reproductive potential in amphibians (Watt and Oldham 1995). Vulnerability to predation also may be increased through impaired swimming ability (Hecnar 1995) or incomplete metamorphosis, which may limit the ability to move on land (Huey 1980).

In temperate Canada, nitrate concentrations in water are usually highest from late fall to spring because of reduced nitrate assimilation by plants (e.g., see Rouse et al. 1999). This peak coincides with the hibernation period, which leads to prolonged nitrate exposure for adult frogs, especially if they hibernate in water (Hecnar 1995). The type of fertilizer applied is also important. Oldham et al. (1997) found that ammonium nitrate fertilizer granules had toxic effects on frogs at application rates of 4–7 grams per square metre, which overlaps with the average application rate (6–9 grams per square metre) in Canada (Statistics Canada 1997; Agriculture and Agri-Food Canada 1998). However, the probability of ammonium nitrate having an acute impact on adult frogs is lessened by the fact that the fertilizer granules dissolve rapidly, thereby decreasing the exposure period, and that fertilizer application generally occurs during daylight, whereas most amphibian migration occurs during darkness (Oldham et al. 1997).

Spring is generally the peak period for fertilizer application and a time when frogs commonly migrate over agricultural land to breeding sites, and so the risk of exposure increases if this movement coincides with a recent fertilizer application (Oldham et al. 1997). This time period also corresponds with an amphibian's vulnerable egg and tadpole stages (Hecnar 1995).

*(continued on next page)*

Water quality data from Canadian agricultural and urban areas suggest that concentrations of nitrate in surface waters exceed critical toxic levels for amphibians for extended periods of time and during sensitive periods of egg and tadpole development. There is therefore a need to reduce both fertilizer runoff and the nitrogen content of sewage effluent. Water quality guidelines for nitrate also need to be reviewed to determine whether they are effective enough to ensure the protection of aquatic life (Rouse et al. 1999). The current Guidelines for Canadian Drinking Water Quality (Health Canada 1996) set the maximum acceptable concentration of nitrate-nitrogen at 10 milligrams per litre to protect human health, but this level does not protect some amphibian species. Currently, the Canadian water quality guidelines for the protection of aquatic life (Canadian Council of Ministers of the Environment 1999) do not specify a maximum acceptable concentration of nitrate.

Nitrite is not considered such a severe environmental problem because it does not usually occur in natural surface water systems at concentrations considered harmful to aquatic organisms (Canadian Council of Resource and Environment Ministers 1987).

## Groundwater

Except in British Columbia and the territories, 90% or more of rural domestic water and much of the water consumed by livestock come from groundwater. Altogether, about 26% of Canadians, or roughly 8 million people, rely on groundwater for their domestic water supply (Government of Canada 1996).

Under natural conditions, nitrate-nitrogen concentrations in groundwater are usually less than 3 milligrams per litre (Henry and Meneley 1993). However, regional surveys of nitrate contamination in groundwater wells in Canada have reported nitrate-nitrogen concentrations greater than the Canadian drinking water quality guideline of 10 milligrams per litre in anywhere from 1.5% to more than 60% of the wells surveyed (Table 4).

In British Columbia, groundwater problems are found mainly in the south coastal region, where the aquifers underlie areas of high rainfall and intensive agriculture. A survey of community and private wells in the Fraser Valley in 1992 and 1993 showed that 9.6% of the wells had nitrate-nitrogen values in excess of 10 milligrams per litre in the winter and 10.1% in the summer. Nearly all of the exceedances occurred in three aquifers — the Abbotsford–Sumas, Hopington, and Langley–Brookswood aquifers, all of which are in heavily developed areas and are overlain by permeable sand and gravel (see Box 4). Most of the exceedances also involved private wells, which were likely exposed to the effects of both agriculture and septic systems.

**Table 4: Summary of nitrate-nitrogen concentrations in rural wells in Canada**

| Source of data | Number of wells sampled | % of wells with nitrate-nitrogen level >10 milligrams per litre | Reference |
|---|---|---|---|
| **British Columbia** | | | |
| Lower Fraser Valley, winter 1992–93 | 239 | 9.6 | Carmichael et al. 1995 |
| Lower Fraser Valley, summer 1993 | 238 | 10.1 | Carmichael et al. 1995 |
| **Alberta** | | | |
| Alberta Agriculture Database | 1 425 | 4.8 | Henry and Meneley 1993 |
| Environmental Centre Database | 12 342 | 4.3 | Henry and Meneley 1993 |
| Alberta Environment Database | 1 692 | 3.3 | Henry and Meneley 1993 |
| Farmstead Water Quality Survey | 813 | 5.7 | Fitzgerald et al. 1997 |
| **Saskatchewan** | | | |
| Saskatchewan Research Council Database | 1 968 | 7.2 | Henry and Meneley 1993 |
| Soil salinity studies | 1 484 | 17.0 | Henry and Meneley 1993 |
| Shallow Ground Water Quality Survey | 184 | 35.9 | Vogelsang and Kent 1997 |
| **Manitoba** | | | |
| Interlake Carbonate Aquifer | 119 | 1.7 | Betcher 1997 |
| Odanah Shale Aquifer | 98 | 19.4 | Betcher 1997 |
| Assiniboine Delta Aquifer | 29 | 3.5 | Buth et al. 1992 |
| **Ontario** | | | |
| Ontario Farm Well Survey, winter 1991–92 | 1 212 | 12.8 | Goss et al. 1998 |
| Ontario Farm Well Survey, summer 1992 | 1 212 | 14.3 | Goss et al. 1998 |
| **Quebec** | | | |
| Portneuf | 70 | 41.4 | Paradis et al. 1991 |
| Potato growing regions | 33 | 63.6 | Giroux 1995 |
| Portneuf | 26 | 34.6 | Paradis 1997 |
| Montérégie | 150 | 2.0 | Gaudreau and Mercier 1997 |
| Orléans Island | 87 | 4.6 | Chartrand et al. 1999 |
| **New Brunswick** | | | |
| Carleton County | 300 | 11–18.2 | Ecobichon et al. 1996 |
| Victoria and Madawaska | 300 | 14.5–22 | Ecobichon et al. 1996 |
| **Nova Scotia** | | | |
| Kings County | 237 | 13.0 | Briggins and Moerman 1995 |
| **Prince Edward Island** | | | |
| Water Well Database | 2 216 | 1.5 | Somers 1998 |
| Dairy Farm Well Survey | 146 | 44.0 | VanLeeuwen 1998 |

Source: Chambers et al. (2001), Table 5.10.

In the Prairie provinces, a dry climate and the generally clayey texture of the soils keep the risk of contamination low. However, exceptions do occur, particularly on irrigated lands and areas near intensive livestock operations that receive large amounts of animal manure. In Alberta, only about 4–6% of domestic wells have nitrate-nitrogen concentrations greater than 10 milligrams per litre (Henry and Meneley 1993; Fitzgerald et al. 1997). The low percentage of contaminated wells may be due to the fact that there are fewer shallow, saturated surface aquifers in Alberta and that, in many parts of Alberta, bedrock aquifers are the preferred water source because of their softer water. In Manitoba, there has been no significant contamination of groundwater by agricultural operations, although a small increase in nitrate-nitrogen concentrations has been detected in portions of the Assiniboine Delta Aquifer where irrigated agriculture is practised (Henry and Meneley 1993). In the Odanah Shale Aquifer, however, 19 of 98 samples had nitrate-nitrogen concentrations above 10 milligrams per litre (Table 4), although naturally occurring nitrate may be contributing in part to high nitrate concentrations (Betcher 1997). In Saskatchewan, however, where shallow unconfined aquifers supply approximately 60% of all farm water supplies, nitrates exceeded the 10 milligrams per litre nitrate-nitrogen guideline in 36% of the private wells sampled in a recent survey (Vogelsang and Kent 1997). Most of the wells with nitrate exceedances had cattle and/or poultry operations near them.

**Box 4: Nitrate contamination of the Abbotsford–Sumas aquifer**

The Abbotsford–Sumas aquifer, located southwest of Abbotsford in southwestern British Columbia and northwestern Washington state, is the largest unconfined aquifer (i.e., one that is overlain by permeable material) in the lower Fraser Valley. It has an area of approximately 100 square kilometres in British Columbia and about the same in Washington (Pacific and Yukon Region Environmental Indicators 2000). Agriculture dominates the land use above the aquifer, with intensive raspberry farming and poultry production accounting for much of it. Urban development covers about 20% of the aquifer surface and continues to spread (Liebscher et al. 1992).

Elevated nitrate concentrations have been observed over a wide area of the aquifer. Because the aquifer is recharged primarily by the infiltration of precipitation, the elevated nitrate concentrations are likely due to the leaching of nitrogen from the agricultural land above. Average precipitation in the Abbotsford area is about 1 500 millimetres per year, and approximately 70% of the total precipitation occurs during the October to March period, when nitrogen removal by crops is low.

A study carried out in the mid-1990s (Wassenaar 1995) estimated that nitrate-nitrogen concentrations exceeded 10 milligrams per litre in as much as 80% of the study area in the aquifer. As Health Canada recommends a maximum concentration of 10 milligrams of nitrate-nitrogen per litre in drinking water, this situation is of considerable concern. The study concluded that nitrate in the aquifer originated primarily from poultry manure, which is frequently applied to raspberry fields as a fertilizer. Chemical fertilizers did not appear to be a significant contributor, nor did septic systems, which, according to estimates, accounted for less than 10% of the nitrate in the aquifer.

Nitrate from fertilizer and manure application is a significant contaminant of groundwater in Ontario. Of 1 212 domestic farm wells surveyed in 1991 and 1992, 12.8% contained nitrate-nitrogen concentrations greater than 10 milligrams per litre during winter and 14.3% during summer (Rudolph and Goss 1993; Goss et al. 1998; Rudolph et al. 1998) (Table 4). A similar survey conducted in the early 1950s found a similar result (T. Bruulsema, Potash and Phosphate Institute of Canada, personal communication).

In Quebec, nitrate contamination of groundwater is associated with areas of intensive potato production. One study found that 21 of 33 domestic wells (63.6%) in potato-growing regions of

Quebec had nitrate-nitrogen concentrations greater than 10 milligrams per litre (Giroux 1995) (Table 4). In another study, for the potato-growing area around Portneuf, of 70 wells sampled between 1990 and 1991, average nitrate-nitrogen concentrations exceeded the guideline of 10 milligrams per litre for 29 wells (41.4%) (Paradis et al. 1991).

In the Atlantic provinces, groundwater contamination occurs mainly in areas where potatoes and corn are produced intensively. In the mid-1980s, depending upon the sampling month, up to 22% of wells in agricultural areas of the Saint John River valley were contaminated (Table 4). In Nova Scotia, nitrate-nitrogen concentrations exceeded 10 milligrams per litre for 13.0% of 237 wells sampled in Kings County, a highly productive agricultural area located at the eastern end of the Annapolis Valley (Briggins and Moerman 1995). In Prince Edward Island, on the other hand, only 1.5% of 2 216 drinking water wells had nitrate-nitrogen concentrations greater than 10 milligrams per litre (Somers 1998); however, a 1997 survey of water samples from 146 dairy farms found that 44.0% of the water samples were above the 10 milligrams per litre nitrate-nitrogen threshold (VanLeeuwen 1998).

### Forests

Concerns about the effects of air pollution on forest health led the Canadian Forest Service to establish the Acid Rain National Early Warning System (ARNEWS) in 1984. This national biomonitoring network was designed to detect early signs of the effects of acid rain on forests to enable action to be taken to forestall anticipated damage. The term “acid rain” encompasses all forms of air pollution: wet and dry deposition of sulphur oxides (SOx), nitrogen oxides (NOx), gaseous pollutants (ozone), and airborne particles.

The latest (1994) analysis of data from ARNEWS concluded that there was no evidence of a large-scale decline in the health of Canadian forests (Natural Resources Canada 1999). Tree mortality was mostly in the normal range of 1–2% and largely due to natural factors. Nevertheless, certain instances of forest damage were observed where pollutants might be involved. For example, in the Bay of Fundy area of New Brunswick, dieback on birch is coincident with the presence of acid fog and high levels of tropospheric ozone (Cox et al. 1996). Needle flecking has been observed on conifers in Nova Scotia and New Brunswick; its cause has yet to be verified. However, there is no evidence to suggest that elevated concentrations of nitrogen oxides or ammonia or direct deposition of nitrogen on vegetation has caused the decline of Canada’s forests.

## Human health effects

Ammonia is not a hazard to human health at the levels that ordinarily occur in the environment. However, exposure to ammonia, especially in aquatic environments, can have several human health impacts. Furthermore, workers involved in the handling and transport of ammonia can be exposed to harmful concentrations of ammonia fumes. The most dangerous consequence of exposure to the gas is pulmonary edema (fluid in the lungs), followed by severe irritation to moist tissue surfaces (Environment Canada 1997b; World Health Organization 1997).

Environmental exposure to harmful levels of nitrates and nitrites, on the other hand, does occur occasionally, with food and nitrate-contaminated water (see the “Groundwater” section under “Toxic

Effects of Nutrient Additions") being the principal sources of exposure. Although nitrates themselves are relatively harmless, about a quarter of the nitrate ingested is converted to nitrites by microorganisms in the saliva. Once in the bloodstream, nitrites impair the blood's ability to carry oxygen by converting hemoglobin into methemoglobin. Ingestion of large amounts of nitrate or nitrite can result in methemoglobinemia, which first shows up as a blue discoloration of the skin but can lead to asphyxia and death when methemoglobin concentrations in the blood reach very high levels (Health Canada 1992; World Health Organization 1997). Infants are much more susceptible to methemoglobinemia than older children or adults. The incidence of methemoglobinemia in Canada is unknown (Health Canada 1997). Nitrates and nitrites are also of concern because nitrites react with amino acids in the stomach to form compounds known as nitrosamines, which have been found to be powerful carcinogens in animal tests (Ramade 1987) and therefore may be carcinogenic in humans (Fraser 1985). However, the National Academy of Sciences in the United States concluded a few years ago that there was no evidence for a role of nitrate in increasing the risk of stomach cancer; on the contrary, recent studies have found a positive role for nitrate in human nutrition of adults (T. Bruulsema, Potash and Phosphate Institute of Canada, personal communication).

Further dangers to human health arise when nutrients, especially nitrogen, stimulate the growth of toxic species of phytoplankton in both fresh and marine waters. Consumption of toxic algae or the organisms that feed on them (e.g., shellfish) can cause serious harm to humans and other terrestrial animals.

In marine waters, toxins produced by microscopic marine algae can reach undesirable concentrations during annual "blooms," which occur when certain species of algae are present in great abundance. The toxins produced by the algae are concentrated further up the food chain when the algae are consumed by shellfish and other marine life. Although the shellfish are only marginally affected by the toxins, a single clam can accumulate enough toxin to kill a human (Anderson 1994). In Canada, serious forms of algal contamination involve three types of poisoning (Health Canada 1997):

- Paralytic shellfish poisoning (PSP) is a result of toxins produced by the dinoflagellate species *Alexandrium fundyense*. When this species blooms, a red coloration of the water may be seen, a phenomenon known as "red tide." PSP toxins may occur in lobsters, clams, oysters, and mussels. Although PSP episodes are rare in Canada, with only a few cases reported per year, PSP continues to be a problem in three regions of the country: the St. Lawrence estuary, the lower Bay of Fundy, and the entire coast of British Columbia (Health Canada 1997).
- Diarrheal (or diarrheic or diarrhetic) shellfish poisoning (DSP) is the result of toxins produced by a type of algae known as *Dinophysis* spp. DSP toxins occasionally occur in clams and mussels. In 1990, the first reported outbreak of DSP in North America occurred in Nova Scotia, after 13 people ate contaminated mussels. Since then, there has been one more confirmed episode of DSP, but many other cases may have occurred, as the symptoms resemble those of the stomach flu (Health Canada 1997).
- Amnesic shellfish poisoning (ASP), so termed because some individuals may suffer permanent short-term memory loss, is caused by domoic acid, a toxin produced by tiny algae called diatoms. ASP has been associated with intense blooms of the diatom species *Nitzschia pungens*. In November and December 1987, 105 acute cases of ASP and three deaths resulted from the consumption of contaminated blue mussels from Prince Edward

> Island (Bates et al. 1989). This incident was the first known occurrence in Canada of human poisoning due to the ingestion of domoic acid.

As a result of concern about shellfish contamination from algae and other sources, the Government of Canada has developed the Canadian Shellfish Sanitation Program and the Shellfish Water Quality Protection Program. The main aims of these programs are to ensure that growing areas for clams, mussels, oysters, scallops, and other shellfish meet approved federal water quality criteria, that pollution sources in these areas are identified, and that all shellfish sold commercially are harvested, transported, and processed in an approved manner. Shellfish are now routinely tested for phytoplankton toxins that could be a serious threat to human health (Todd 1990; A. Menon, Environment Canada, personal communication).

In fresh water, toxic blooms are usually made up of blue-green algae. In Canada, blooms of this kind usually occur in late summer and early autumn (Granéli et al. 1990; Nascimento and Azevedo 1999). Once a bloom occurs, its toxicity can vary over time. In some cases, blue-green algal scum can remain toxic even after drying out on shorelines. Many blue-green algal species can fix atmospheric nitrogen gas in their cells; hence, in waters with low nitrogen concentrations, blue-green algae often outcompete other algae and become the dominant algal form.

Blue-green algal toxins, which are released from the algae when the cells age and break down, affect either the nervous system or the liver (Kotak et al. 1993). Animals that drink water containing blue-green algal neurotoxins can die from respiratory arrest in as little as 5 minutes. The amount of tainted water needed to kill an animal depends on such factors as the type and amount of toxin produced by the cells, the concentration of the cells, and the species, size, sex, and age of the animal (Carmichael 1994).

Globally, only one human death from blue-green algal poisoning has been confirmed. The low incidence of human death is largely due to an aversion to the foul appearance and odour of water that is contaminated by phytoplankton blooms rather than to any greater physical resistance to blue-green algal toxins. However, accidental exposures may occur during recreational activities, such as swimming, canoeing, and sailing. Symptoms associated with the ingestion of these organisms may include fever, headache, dizziness, stomach cramps, vomiting, diarrhea, skin and eye irritations, sore throat, and swollen lips. Children are at higher risk because they spend more time in the water than adults, are more likely to swallow contaminated water, and may have a lower tolerance for toxic algae (Health Canada 1997). Consumption of water containing low concentrations of blue-green algal toxins over the course of a lifetime may also contribute to the development of cancer (Carmichael 1994).

Toxic blue-green algae have been found in lakes in Alberta, Saskatchewan, Manitoba, and Ontario (Canadian Council of Resource and Environment Ministers 1987). Due to the risks associated with drinking water contaminated with algal toxins, Health Canada has proposed a guideline of 1.5 micrograms per litre for microcystin-LR, a liver toxin, in drinking water (Health Canada 1998). Water supplies contaminated with toxic blue-green algae can often be treated with certain algicides. However, death of the algae may result in the release of toxins into the surrounding water (Carmichael 1994; Jones and Orr 1994).

## Socioeconomic effects

The occurrence of toxic algal blooms has forced the closure of many shellfish fisheries in Canada's coastal regions. In British Columbia, for example, as of July 1999, 246 areas, encompassing an area of about 1 050 square kilometres, were closed to shellfish harvesting (Environment Canada 2001); although most of these closures were the result of contamination by pathogens, several were directly due to the accumulation of algal toxins by shellfish. The area of British Columbia's coastline that has been closed to shellfish harvesting has increased substantially since Environment Canada began assessing the sanitary quality of shellfish growing waters on a regular basis in the early 1970s (Pacific and Yukon Region Environmental Indicators 1998), and only part of this increase can be attributed to an increase in monitoring activities. With the value of all wild commercial shellfish fisheries combined estimated at more than $110 million in 1997, the closure of such a large number of harvesting zones represents a substantial loss in potential earnings to the B.C. shellfish industry and the communities dependent on it.

On the Atlantic coast (excluding Quebec), 35% of the area suitable for shellfish harvesting was closed in 1995, at a loss of about $10–12 million to the local economy (Chambers et al. 1997). In 1999, the area closed was 2 065 square kilometres (Environment Canada 2001). In Quebec, of a total of 196 shellfish zones evaluated in 1999, 114 (58%) were permanently closed, and a further 21 (11%) were closed from 1 June to 30 September (Environment Canada 1999a). It is unclear as to what proportion of the closures were due to biotoxins.

Little is known about the impact of biotoxins on finfish aquaculture, but there is potential for harm. As caged fish cannot avoid areas of blooms, fish kills could result from direct uptake of the toxins, depletion of oxygen in the water, or physical disruption of gill function. According to Percy (1996), phytoplankton blooms are a serious threat to the $100-million aquaculture industry in the Bay of Fundy. As a result, water temperatures and phytoplankton populations are regularly monitored in an effort to prevent any problems. Wild fish kills can also result from the transfer of toxins through the food web during intense blooms. Anchovies in British Columbia waters, for example, have been known to be affected by domoic acid.

In rural areas, blue-green algal blooms that develop in fresh water can be a hazard to livestock. During the 1960s and 1970s, toxic algae in the Prairie provinces and Ontario were implicated in the deaths of many animals, including about 30 dogs and a number of horses and cows. As a result of these incidents, the Canadian Council of Ministers of the Environment has advised against watering livestock from lakes, ponds, or streams that contain heavy growths of blue-green algae (Canadian Council of Resource and Environment Ministers 1987).

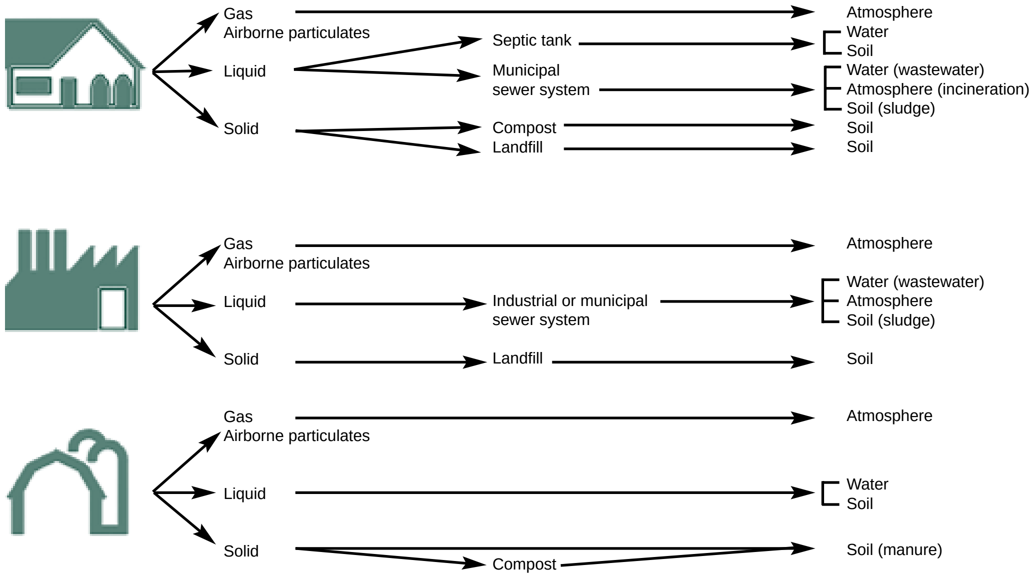
Effects on wildlife resources include fish kills caused by blue-green algae (Gorham and Carmichael 1980; Skulberg et al. 1984) and a general decline in the reproductive success of fish, as oxygen depletion causes fewer eggs to hatch and reduces the area of habitat available for reproduction. Toxic algae have also poisoned waterfowl populations and contributed to outbreaks of avian botulism (T. Leighton, Canadian Cooperative Wildlife Heath Centre, Saskatoon, personal communication).

# 4

# Sources of Nutrient Additions

Most of the nitrogen and phosphorus entering the environment from human activities comes from municipal and rural wastewaters, agriculture, and industrial wastes (Figure 6), with significant contributions also coming from aquaculture and forestry. Much of it eventually ends up in surface waters, through direct discharge, as in the case of municipal and industrial effluents, through groundwater and surface runoff, as in the case of nutrients leached from agricultural croplands, or through atmospheric deposition, as in the case of particles and gases emitted to the air from croplands, industrial smokestacks, and vehicle tailpipes.

**Figure 6: Municipal, agricultural, and industrial sources and fates of excess nitrogen and phosphorus in the environment**



Source: Chambers et al. (2001), Figure 3.1.

This chapter describes and quantifies the processes by which these sources contribute to nutrient enrichment. An overview of nutrient loadings to surface water and groundwater from various sources is given in Table 5.

**Table 5: Comparison of nutrient loadings to surface water and groundwater from various sources in Canada, 1996**

| Nutrient source | Phosphorus loading (thousands of tonnes per year) | Nitrogen loading (thousands of tonnes per year) |
|---|---|---|
| **Municipal** | | |
| Municipal wastewater treatment plants | 5.6 | 80.3 |
| Sewers (storm and combined sewer overflows) | 2.3 | 11.8 |
| Septic systems | 1.9 | 15.4 |
| **Industry** | 2.0 | 11.8 |
| **Agriculture** | | |
| Inputs | 442 | 2 784 |
| Removed | 386 | 2 491 |
| Runoff | n/a | n/a |
| **Aquaculture** | 0.5 | 2.3 |
| **Atmospheric deposition** | n/a | 182 ($NO_3^-$ and $NH_4^+$) |

Notes:
Industrial data are not available for New Brunswick, Nova Scotia, or Prince Edward Island, and therefore this value is underestimated.
Data for septic systems represent the amount of nutrients that are released after retention by the septic tank and drain field has been taken into account.
Agricultural inputs include commercial fertilizer, livestock manure, atmospheric deposition, biosolids, and fixed nitrogen by legumes.
Agricultural removals include crop harvesting and uptake of nutrients by pasture vegetation.
n/a: not available.

Source: Provisional data provided by Chambers et al. (2001).

## Municipal and rural wastewaters

Municipal wastewater, or sewage, comes from households, office buildings, and small to medium-sized industries and is a complex mixture of suspended solids, microorganisms, and debris; some 200 chemicals have also been identified in this waste stream in Canada (Government of Canada 1996). The nutrients in this mix come from human waste, household cleaning products such as laundry detergent, automatic dishwashing detergent, and general cleaners, and industrial by-products. Human waste contributes more than 90% of the household nitrogen loadings, with most of the nitrogen in the form of ammonia. Human waste is also the largest source of phosphorus in sewage, followed at a distant second by automatic dishwashing detergent.

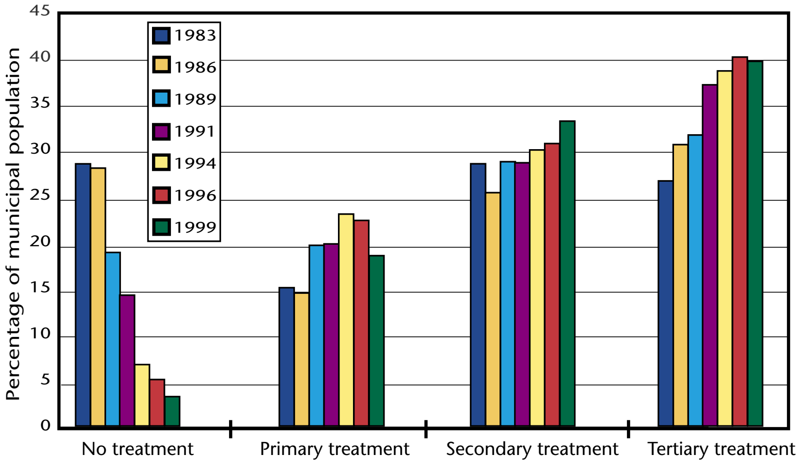
Almost all municipal wastewater in Canada undergoes one or more of the following levels of treatment:

- *primary treatment*, which uses physical processes to remove suspended solids;
- *secondary treatment*, which uses biological processes to break down organic material and remove additional suspended solids; and
- *tertiary treatment*, which uses advanced chemical or biological treatment to remove specific compounds or materials that remain after secondary treatment.

Some of the nutrients in wastewater can be removed by settling, but a precipitating agent such as alum can also be added at any of these stages to increase phosphate removal. Effective nitrogen removal requires the addition of specialized bacteria during secondary treatment. Higher treatment levels generally imply lower nutrient loadings to the receiving waters, but even primary treatment can reduce loadings substantially.

The percentage of Canadians served by wastewater treatment has been increasing; in 1999, 73% of Canadians were served by municipal sewer systems (Environment Canada 2001). An additional 25% relied on septic beds for sewage treatment. The remaining 2% were in communities with populations less than 1 000 and likely serviced by lagoons. Of those with sewers, 97% (21.9 million Canadians) had some level of wastewater treatment provided in 1999, compared with 72% in 1983 (Figure 7). The remaining 3% (approximately 0.8 million Canadians) were serviced by sewage collection systems that discharged untreated sewage directly into lakes, rivers, or oceans (Environment Canada 2001). Discharges of untreated sewage can also occur in municipalities served by combined sewer systems. These systems carry both raw sewage and storm water; during periods of high rainfall or snowmelt, however, they are often allowed to overflow directly into receiving waters to prevent sewage from backing up into basements or overloading the treatment facility. Combined sewer overflows can be a major source of nutrient loadings.

**Figure 7: The proportion of Canada's population with municipal wastewater treatment, 1983–1999**



Notes:

(i) Refers only to municipal population served by a municipal sewer system.

(ii) The MUD survey collects water- and wastewater-related information from Canadian municipalities having populations of 1000 or more, every two or three years. Municipalities self-report their wastewater treatment levels based on the definitions provided in the MUD survey. Therefore, some municipalities may report treatment levels that are different from those reported by other agencies (i.e., provinces/territories, regions, and nongovernmental organizations) based on differences in treatment level definitions (see Fig. 8 for MUD definitions). Furthermore, MUD occasionally amalgamates several different treatment facilities for a municipality into one overall level of treatment, when more than one facility exists in a municipality.

Source: Environment Canada, Municipal Water Use Database (MUD).

The level of sewage treatment varies greatly across Canada, but, as Figure 8 shows, it is generally improving as more municipalities upgrade their wastewater treatment facilities. In 1999, secondary and tertiary treatment were provided to 78% of the sewered population (17.6 million Canadians), up from 56% in 1983. Primary treatment increased from 16–17% in 1983 to 23% in 1994, but has decreased to approximately 19% in 1999 (4.3 million Canadians) as a result of municipalities upgrading their wastewater treatment plants (e.g., the Greater Vancouver Regional District). Much of this change occurred in Quebec, where the population served by wastewater treatment increased from 2% in 1980 to 75% in 1991 (Ministère de l'Environnement et de la Faune du Québec 1995). The level of treatment across Canada tends to be highest in inland areas, where sewage is discharged to lakes or rivers, and lowest in coastal areas, where it is discharged into the ocean or estuaries.

**Figure 8: The number of Canadians in each region of Canada served by sewage treatment, 1983–1999**

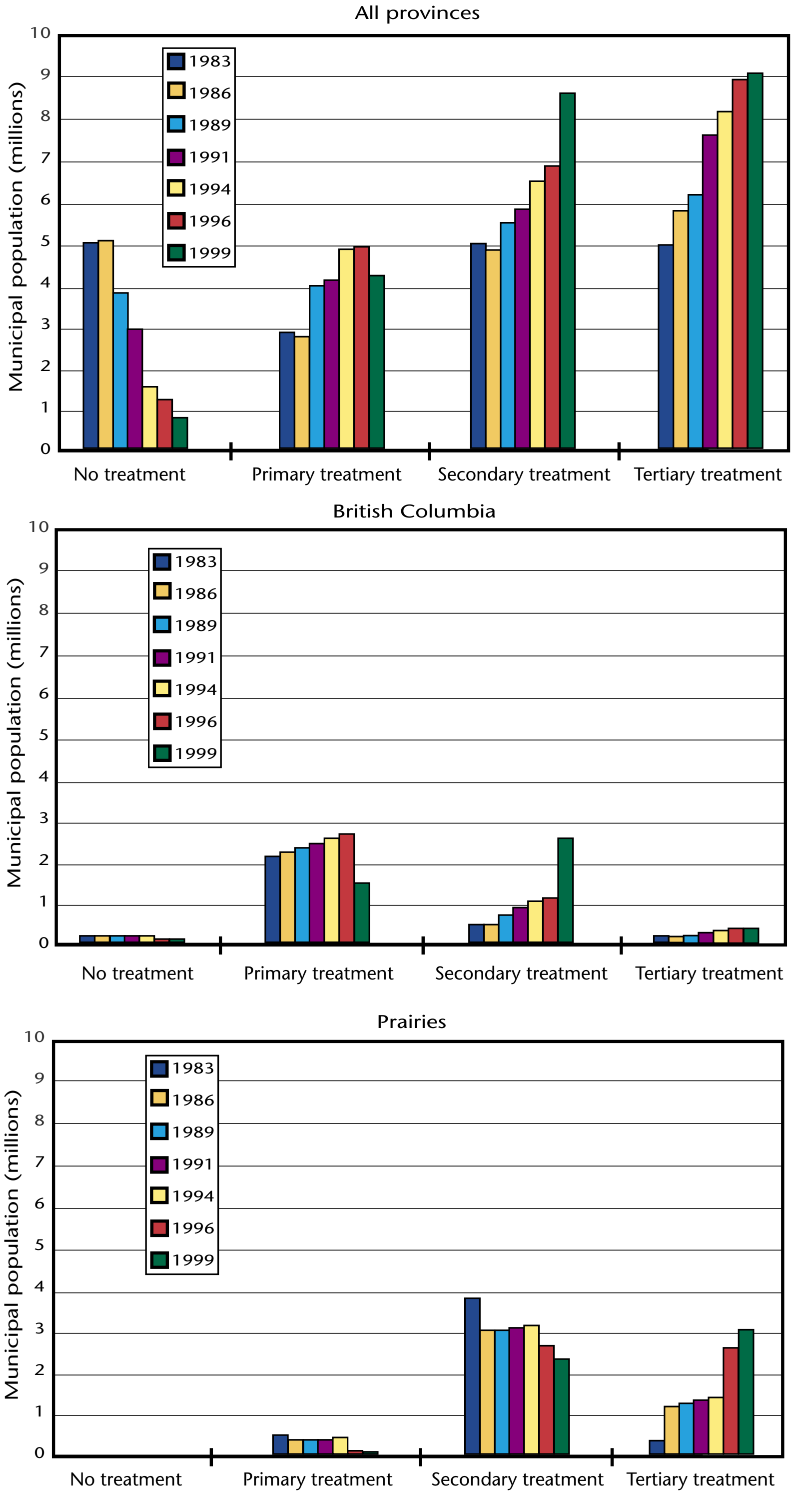


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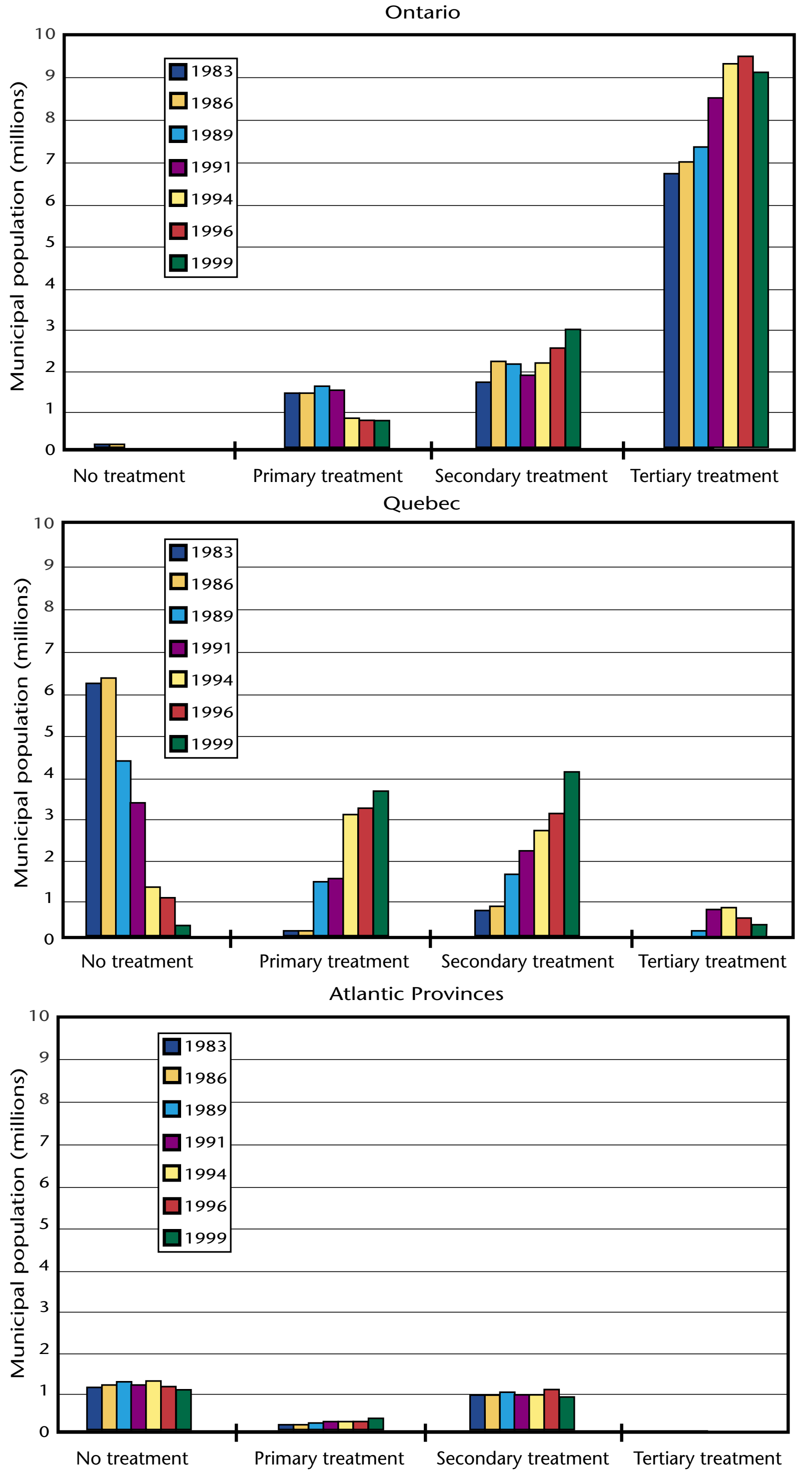
**Figure 8: The number of Canadians in each region of Canada served by sewage treatment, 1983–1999**



Notes:

(i) The slight decrease in tertiary treatment in Ontario and Quebec between 1996 and 1999 likely results from the change in reported data verification procedures for the MUD survey starting in 1996.

(ii) The MUD survey defines primary treatment as any form of mechanical sewage treatment, secondary treatment as biological sewage treatment or waste stabilization ponds, and tertiary treatment as some form of sewage treatment providing a higher level of treatment than secondary treatment.

(iii) Readers should be aware that use of definitions of wastewater treatment levels that are different from those used in the MUD survey would yield different results from those represented in Figure 8. Under the MUD survey definitions, mechanical screening could be considered as primary treatment.

Source: Environment Canada, Municipal Water Use Database (MUD).

In 1999, roughly 82 750 tonnes of total nitrogen (i.e., nitrogen in all its chemical forms) were released to surface waters in Canada through municipal wastewater discharges — a 24% increase over 1983. Because of their large populations, Ontario and Quebec discharged the largest amounts. In 1996, overall, the total amount of nitrogen released from municipal wastewater was 71 000 tonnes to inland waters, 5 100 tonnes to Pacific coastal waters, and 5 500 tonnes to Atlantic coastal waters.

In 1999, an estimated 4 950 tonnes of total phosphorus were released to surface waters in Canada from municipal wastewater treatment plants — a 44% decrease since 1983. The total phosphorus loading from Ontario municipal wastewater treatment plants (1 000 tonnes in 1996) was similar to that from British Columbia (1 000 tonnes) and the Atlantic provinces (900 tonnes), even though the population of Ontario is three times larger than that of British Columbia and five times larger than that of the Atlantic region (Figure 9). Ontario releases much less phosphorus, on a per capita basis, because most of its population is served by tertiary treatment, whereas many coastal populations have either no treatment or primary treatment (Table 6). In 1996, the total amount of phosphorus released from municipal wastewater overall was 4 200 tonnes to inland waters, 460 tonnes to Pacific coastal waters, 890 tonnes to Atlantic coastal waters, and 2 tonnes to Arctic coastal waters.

Not all of these amounts of nitrogen and phosphorus are present in forms that are bioavailable (i.e., available in a form that can be used by phytoplankton and other algae and plants, and thus able to cause eutrophication). For nitrogen, about 60% of the total loadings is bioavailable, in the form of free ammonia, whereas for phosphorus, between 65% and 100% of the total loadings is bioavailable (Tchobanoglous and Burton 1991).

*Sewage sludge*, which is produced at all three levels of wastewater treatment, refers to the organic and inorganic solids resulting from the decomposition and settling of wastewater as it undergoes treatment (Warman 1997). Primary sludge consists of materials that settle out during the sedimentation process of primary sewage treatment. Primary treatment produces approximately 80 grams of sludge solids per person per day, secondary treatment yields about 115 grams of sludge solids per person per day, and tertiary treatment typically produces about 145 grams of sludge solids per person per day (Black et al. 1984).

Because sewage sludge typically contains about 4% nitrogen and 2.5% phosphorus (Webber and Bates 1997), it can be a desirable nutrient additive to agricultural land. However, sludge derived from industrial effluent may have high concentrations of heavy metals, pathogens (Webber and Bates 1997), or organic chemicals. Most provinces have guidelines for the application of biosolids (i.e., sludge that is suitable for beneficial uses such as crop fertilizer) to agricultural land. These aim to match the nutrient content of the biosolids with the nutrient demands of the crop while limiting the accumulation of heavy metals and micronutrients in agricultural soils.

**Figure 9: Phosphorus loadings as a result of municipal effluent releases for each region of Canada, 1983–1996**

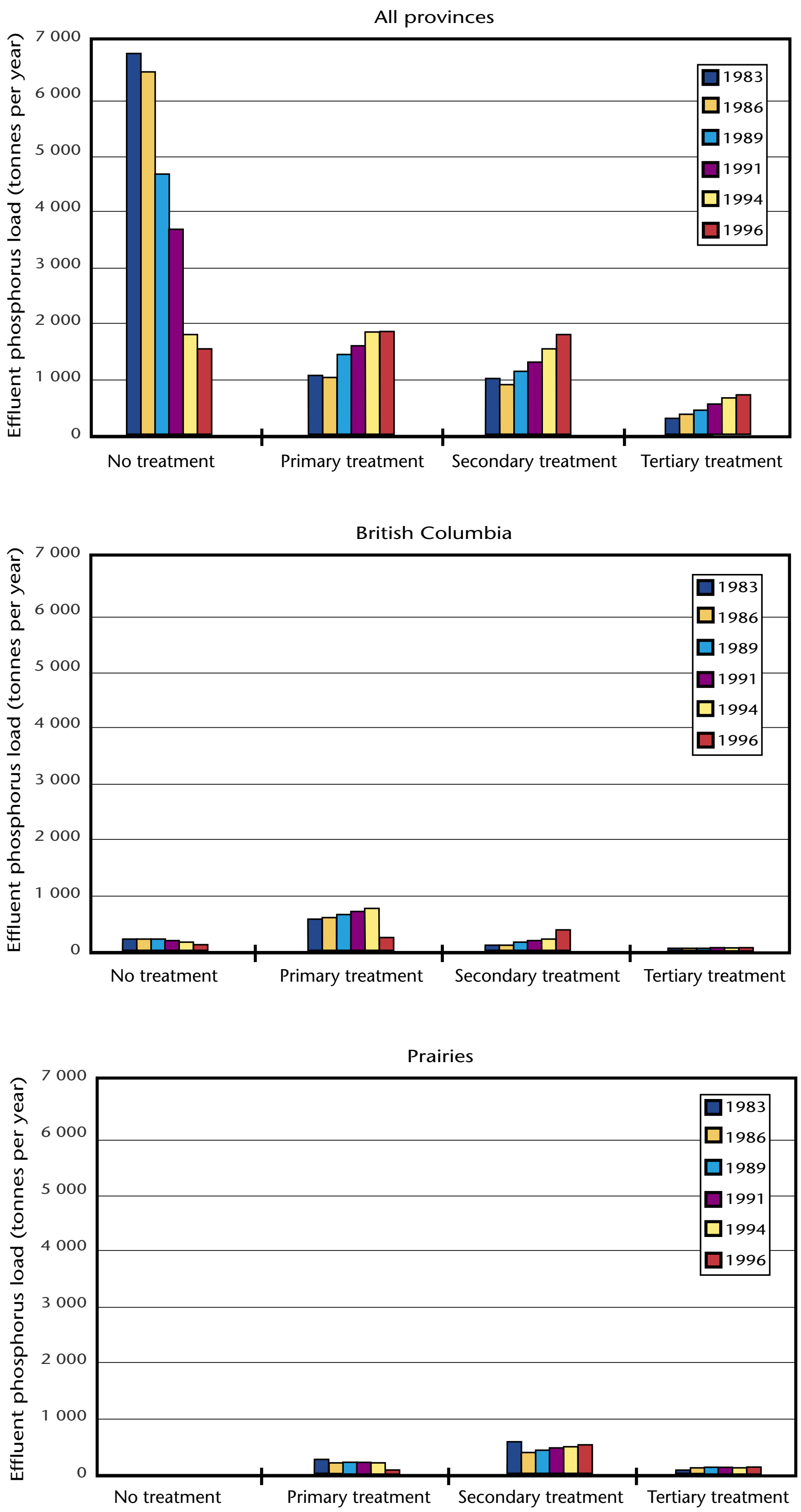


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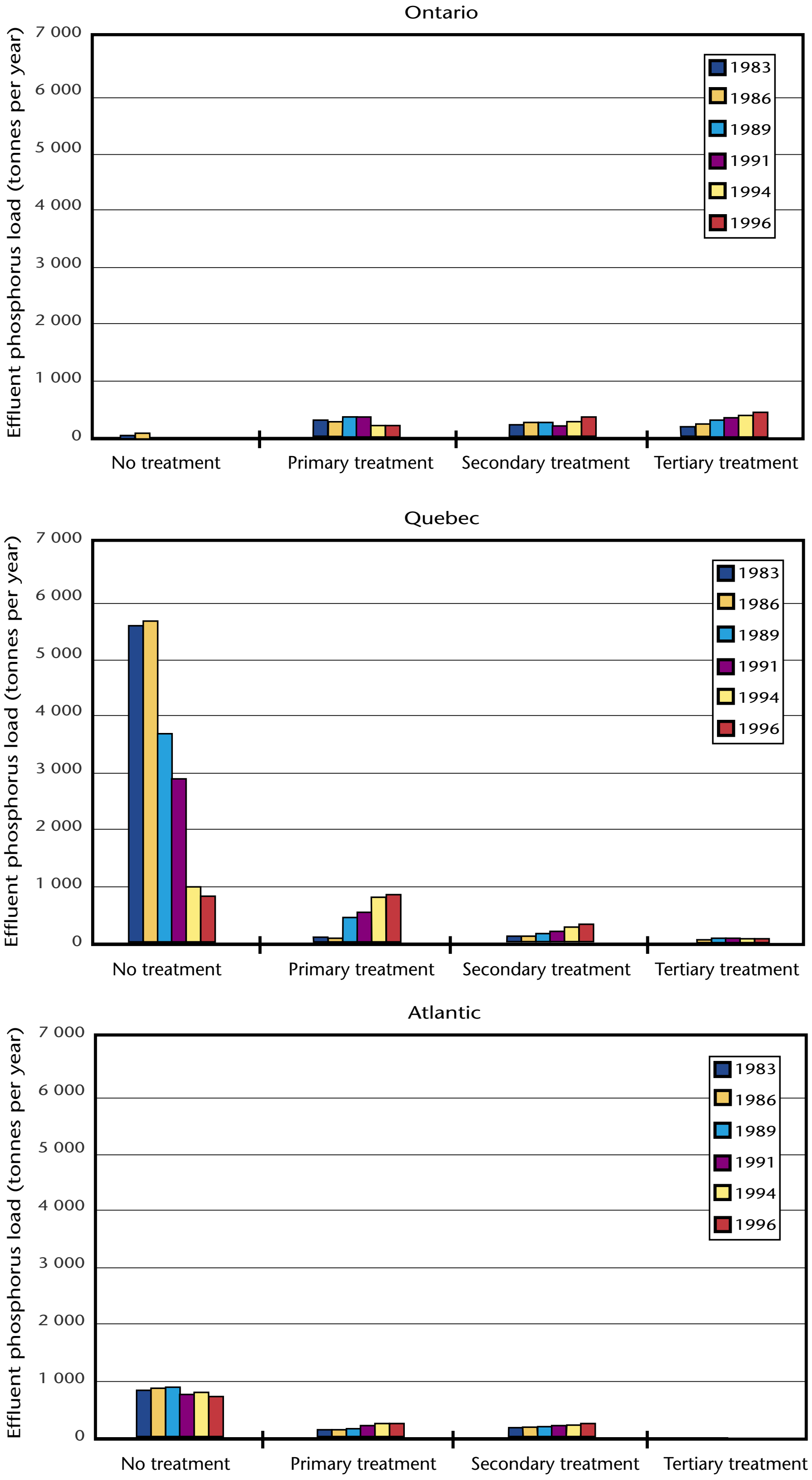
**Figure 9: Phosphorus loadings as a result of municipal effluent releases for each region of Canada, 1983–1996**



Note: Readers should be aware of notes for figures 7 and 8 regarding the database and definitions on which this figure is based.

Source: Chambers et al. (2001), Figure 3.5.

**Table 6: Total loadings of phosphorus in the final effluent and its removal efficiency for various levels of wastewater treatment**

| Treatment type | Phosphorus removal? | Number of facilities sampled | Effluent total phosphorus load (grams per person per day) | Total phosphorus removal efficiency (%) |
|---|---|---|---|---|
| Primary | no | 9 | 1.71 | 36.3 |
| | yes | 19 | 0.75 | 75.5 |
| | **Average** | **28** | **1.06** | **62.9** |
| Secondary | no | 46 | 1.03 | 59.0 |
| | yes | 137 | 0.42 | 88.4 |
| | **Average** | **183** | **0.58** | **81.0** |
| Lagoons | no | 45 | 0.78 | 65.5 |
| | yes | 76 | 0.20 | 92.5 |
| | **Average** | **121** | **0.42** | **82.4** |
| Tertiary | no | 2 | 1.02 | 58.7 |
| | yes | 33 | 0.15 | 94.7 |
| | **Average** | **35** | **0.20** | **92.7** |

Note: Values were calculated from data presented in a 1991 survey of Ontario municipal wastewater treatment plants (Ontario Ministry of Environment and Energy 1993). Removal efficiency was calculated as the difference between the influent and effluent load, expressed as a percentage of the influent load.

Source: Chambers et al. (2001), Table 3.1.

With the costs of landfilling increasing, agricultural application is becoming the most economical sludge management option. In the early 1980s, 500 000 tonnes per year (dry weight) were produced; on average, 42% of this sludge was applied to agricultural land, and the rest was either incinerated or landfilled (Organisation for Economic Co-operation and Development 1995). This amounted to 8 400 tonnes of nitrogen and 5 300 tonnes of phosphorus from sewage sludge being applied to agricultural land in Canada every year in the early 1980s.

About 8 million Canadians, slightly more than one-quarter of the population, are served by septic systems. In many localities, septic disposal systems are too numerous for the land base. Many are also poorly maintained or have been built too close to shorelines or in areas where rock or soil conditions are unsuitable. Based on a 1996 population, an estimated 15 400 tonnes of nitrogen and 1 900 tonnes of phosphorus were released from septic systems in Canada. These discharges can be sources of contamination to groundwater and, ultimately, to surface waters.

## Agriculture

Application to agricultural lands of chemical fertilizer or manure in excess of plant requirements can lead to a buildup of nutrients in the soil and their eventual loss to surface waters, groundwater, or the atmosphere.

Supplementary fertilizer nutrients are used to increase crop yields. Nitrogen fertilizers are based on ammonia, which can be used directly as a fertilizer or converted to solid compounds (urea, ammonium phosphate, ammonium nitrate, and ammonium sulphate) or to nitrogen solutions. Phosphate fertilizers are produced from phosphate rock. In 1996, 1 576 000 tonnes of nitrogen and 297 000 tonnes of phosphorus as fertilizer were applied to cropland in Canada. In addition, 384 000 tonnes of nitrogen and 139 000 tonnes of phosphorus were applied as manure (Agriculture and Agri-Food Canada 1998).

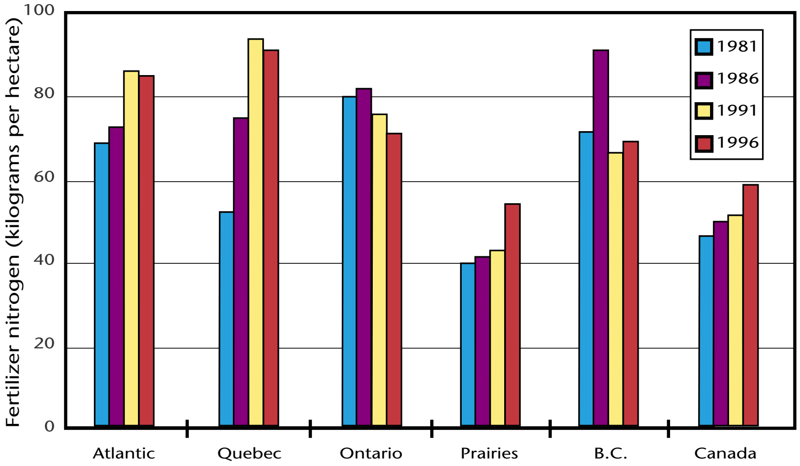
Manure consists of undigested feed (liquid and solid), metabolic waste, bedding material, and waste feed and water. In 1996, approximately 4.7 million beef cattle, 1.2 million dairy cattle, 11 million hogs, 102.3 million poultry, and 3.2 million other livestock were reared in Canada (Statistics Canada 1997). Not surprisingly, manure storage and disposal are management considerations on many Canadian farms.

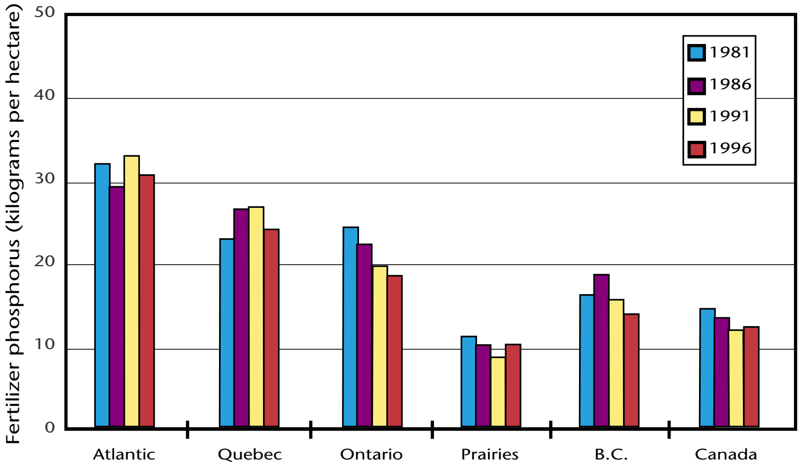
Almost all manure produced on Canadian farms is applied to agricultural land (Patni 1991). Manure supplies soils with both nutrients and organic matter. Depending upon the type of livestock and the feed being used, fresh manure can contain 50–80% of the nitrogen and phosphorus originally present in the feed. However, not all nutrients in manure are immediately available to crops. Some are tied up in organic forms and become available over time as the material decomposes, thereby acting as a nutrient source over several years. Average manure application in 1996 ranged from an estimated 114 kilograms of nitrogen per hectare in Quebec to 301 kilograms of nitrogen per hectare in British Columbia and 38 kilograms of phosphorous per hectare in the Atlantic to 184 kilograms of phosphorus per hectare in British Columbia (Figure 10). These figures do not include nutrient loadings from beef cattle manure, since these animals are commonly left out to pasture for most of the year.

Nitrogen fixed from the air by legume crops can add significantly to the soil’s nitrogen supply. The ability of legumes to improve soil nitrogen concentrations is the basis for crop rotation schedules on most farms. The nitrogen fixed by legumes, however, is tied up in the plant and must decompose and mineralize to be available to subsequent crops (Gleig and MacDonald 1998). Atmospheric nitrogen fixation rates for legume species range from 53 kilograms of nitrogen per hectare per year for chickpeas to 100 kilograms of nitrogen per hectare per year for clover (F. Selles and R. Lemke, Agriculture and Agri-Food Canada, personal communication). In 1996, nitrogen input from atmospheric nitrogen fixation by legumes ranged from 20 000 tonnes of nitrogen in the Atlantic region to 476 000 tonnes of nitrogen in the Prairies, for a total of 773 000 tonnes of nitrogen fixed by legumes in Canada.

The difference between nutrient inputs (from fertilizer, manure, nitrogen fixation, atmospheric deposition, sewage biosolids, and seeds and planting material) and outputs (from crop and fodder production) indicates either a nitrogen surplus (i.e., input greater than output) or deficit (i.e., input less than output). For all agricultural land in Canada, annual inputs in 1996 (2.8 million tonnes of nitrogen and 442 000 tonnes of phosphorus) exceeded outputs (2.5 million tonnes of nitrogen and 386 000 tonnes of phosphorus) by 10.7% and 12.7%, respectively (Chambers et al. 2001). These are average values, of course, and individual regions may have had either surpluses or deficits. Nevertheless, this national surplus of roughly 0.3 million tonnes of nitrogen and 56 000 tonnes of phosphorus sets the stage for nutrient losses to the environment.

**Figure 10: Nitrogen and phosphorus added as fertilizer (1981–1996) and manure (1991–1996) to Canada's cultivated land**





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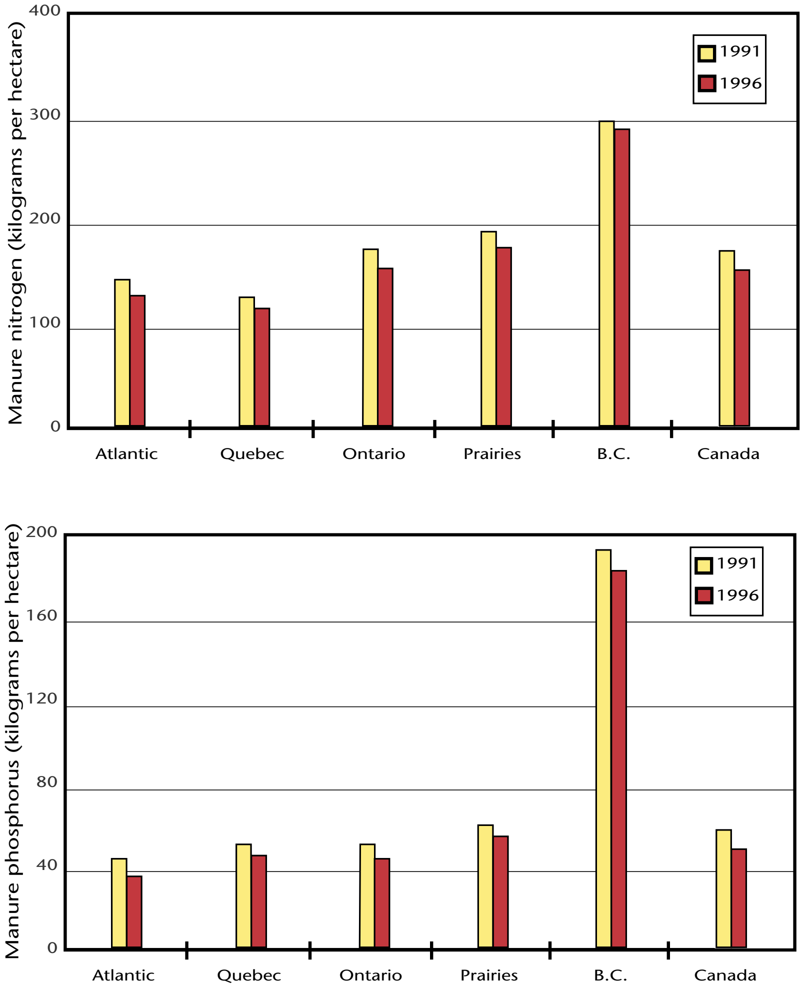
Leaching of nitrogen from fields is strongly affected by a growing crop. During crop growth, there is both little downward movement of water in the soil and a continual uptake of nitrogen by the plants, and thus conditions are unfavourable for the leaching of nitrogen (Gleig and MacDonald 1998). However, after a crop has been harvested, nitrogen uptake decreases, nitrogen is released through the breakdown of crop residue, and leaching increases. Most leaching losses occur between the harvest of one crop and the emergence of the next. Generally, less leaching takes place from manured fields than from commercially fertilized fields, in part because some of the manure's nitrogen escapes to the air as ammonia, and a higher proportion of its nitrogen is tied up in organic matter (Gleig and MacDonald 1998).

**Figure 10: Nitrogen and phosphorus added as fertilizer (1981–1996) and manure (1991–1996) to Canada's cultivated land**



National estimates are not available for the quantity of nitrogen and phosphorus lost to surface waters and groundwater from agricultural lands, from manure storage facilities, or from livestock housing and handling facilities.

Agricultural nitrogen losses to the atmosphere occur as a result of the release of ammonia from livestock manure and fertilizers and through the breakdown of nitrates in the soil to produce nitrous oxide, nitric oxide, or nitrogen gas. There is also some ammonia loss from the decomposition of crops. Additional losses occur as a result of fuel combustion and biomass burning.

In 1995, Canadian agricultural emissions of nitrogen in the form of ammonia were estimated to be 570 000 tonnes (Vézina 1997), with manure accounting for 87% of this total and fertilizer making up the balance. Of the manure emissions, cattle accounted for 59%, poultry for 21%, and pigs for 19% of the ammonia-nitrogen.

## Industrial discharges

Industrial wastes may be released on-site to the atmosphere, land, surface waters, or groundwater or may be transferred off-site for application to land, disposal in landfills, or treatment in municipal wastewater plants. Most light industries discharge their wastewater into municipal sewage systems and dump their solid waste in municipal landfills. Pulp mills, mining operations, large manufacturing plants, and other large industries that dispose of their waste independently must obtain operating permits from the government of the province or territory in which their facilities are located. These generally stipulate the quantity and/or quality of waste that can be discharged.

For the 1988–1998 period, wastewater discharges to surface waters from industries with operating permits included an estimated 7 588 tonnes of nitrate-nitrogen per year and 4 231 tonnes of ammonium-nitrogen per year. In addition, the National Pollutant Release Inventory indicated that 6 421 tonnes of nitrogen as ammonia were injected underground in 1996 (Environment Canada 1996). This process involves injecting wastes into known geological formations, generally at great depths, and largely occurred in Alberta and, to lesser extent, Saskatchewan. It was largely associated with the petroleum refining and organic chemical manufacturing sector in Alberta and the mining industry in Saskatchewan.

At least 2 048 tonnes of total phosphorus per year were discharged to surface waters from permitted industries in Canada. Reporting years differ by province but are within the 1988–1998 time period.

Industries release nitrogen to the atmosphere as nitrous oxide, other nitrogen oxides, and ammonia. In 1995, industrial combustion-related emissions of nitrous oxide accounted for 3 000 tonnes of nitrogen (Chambers et al. 2001), and combustion-related emissions of nitric oxide and nitrogen dioxide from industrial sources were 86 000 tonnes of nitrogen (Environment Canada 1999c). The petroleum/petrochemical industry accounted for emissions of 113 000 tonnes of nitrogen oxides.

Ammonia is released to the atmosphere by chemical and chemical products industries. According to Vézina (1997), 27 000 tonnes of nitrogen as ammonia were released to the atmosphere by Canadian industries in 1995. Of this, 33% was produced by industries engaged in the manufacture of chemicals and 31% by the petroleum/petrochemical industry.

## Aquaculture

Aquaculture, the cultivation of fish, molluscs, crustaceans, plants, and other aquatic organisms, is currently a small industry in Canada. However, it is rapidly expanding and now includes the production of approximately 45 fish and 14 invertebrate species (see Chambers et al. 2001, Table 3.12). In 1996, 53 000 tonnes of finfish and 19 000 tonnes of shellfish were harvested as a result of aquaculture in 10 provinces, representing a value of $350 million (see Chambers et al. 2001, Table 3.13). Of this production, 58% took place in marine environments and 42% in freshwater environments (see Chambers et al. 2001, Table 3.14). The majority of operations were located in either British Columbia or New Brunswick.

Aquaculture operations range from small private ponds to large cage cultures that produce thousands of tonnes of fish per year. Nutrient releases from fish production result from excretion of dissolved or solid waste and from unconsumed feed. The quantity and quality of the feed largely determine the extent of nutrient loss to the environment, because they affect both feed wastage and excretion losses (Persson 1991; Cho and Bureau 1997).

### Box 5: Impacts of aquaculture on Heney Lake, Quebec, 1993–1998

Located in the Outaouais region of Quebec, Heney Lake supports a valuable trout fishery. The lake has an area of 12.4 square kilometres and a maximum depth of 30–33 metres. In the early 1990s, phosphorus concentrations in Heney Lake were moderate, and the lake was mesotrophic.

In 1993, a fish farm opened on a tributary of Heney Lake. In its five years of operation, the fish farm's effluent was implicated in the near doubling of the lake's phosphorus concentrations. Quebec's Ministère de l'Environnement et de la Faune reported that the fish farm's nutrient-rich wastewater added over 400 kilograms of phosphorus to the lake annually via the lake's tributary. The wastewater's high nutrient concentration was attributed to the presence of waste food pellets in the effluent. The elevated phosphorus concentrations increased the abundance of both planktonic algae and larger plants, including filamentous algae, in the deep waters (Bird and Mesnage 1996). They were also associated with a dramatic decrease in water clarity and oxygen concentrations.

These changes raised concerns that the cold, deep waters of the lake might be unsuitable for habitation by lake trout during July because the concentration of oxygen was too low (Prairie 1994). The lowered oxygen levels could also have a long-term effect by reducing the growth and reproductive rates of sensitive species such as lake trout. In addition, the growth of macrophytes was reported to be destroying the spawning sites of lake trout.

In November 1998, the Quebec government closed the fish farm in the hope of avoiding further deterioration in the water quality of Heney Lake.

### Box 6: The role of aquaculture in eutrophication of coastal waters

Because aquaculture operations produce substantial amounts of fish and feed wastes, concerns have been raised about the potential for eutrophication in coastal waters where these operations are based (Wildish et al. 1990). Studies of operations in the Bay of Fundy (Wildish et al. 1990) and along the B.C. coast (Taylor et al. 1994; Black and Forbes 1997), however, have not shown any significant effect on nutrient loadings or increases in the abundance of phytoplankton. Some potential does appear to exist, though, for localized effects immediately underneath the cages that retain the fish (Fisheries and Oceans Canada 1997). Of the approximately 70% of nutrients that are typically lost to the environment from aquaculture operations, about 32% of the nitrogen and 63% of the phosphorus are in the form of particles that end up in the sediment (Hall et al. 1992). These nutrient-rich particles can increase oxygen demand in the sediment, which, in turn, increases the release of nutrients from the sediment (Hall et al. 1992; British Columbia Environmental Assessment Office 1997). On Canada's east coast, oxygen demand has been found to be four times higher under aquaculture pens than at reference sites (Hargrave et al. 1993).

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Mild enrichment from the sediments stimulates the abundance and biomass of the plants and animals that inhabit the seafloor directly under the pens. If, however, aquaculture pens are poorly sited, pollution-sensitive species can be lost and the seafloor under the cages can become dominated by organisms that are more tolerant of organic pollution, such as various species of worms that inhabit oxygen-depleted sediments (British Columbia Environmental Assessment Office 1997; Fisheries and Oceans Canada 1997).

Studies of rainbow trout and Atlantic salmon aquaculture have shown that only about 20–30% of nutrients added to an aquaculture operation are incorporated into fish biomass and removed at harvest. The other 70–80% of added nutrients are lost to the environment in the form of metabolic waste, feces, and uneaten food fragments (e.g., see Levings 1994; MacIsaac and Stockner 1995). These nutrient losses may contribute to eutrophication in both freshwater (see Box 5) and marine (see Box 6) ecosystems.

In an assessment of nutrient loadings from salmon operations in British Columbia, Fisheries and Oceans Canada (1997) estimated losses of 43 kilograms of nitrogen and 9.5 kilograms of phosphorus per tonne of fish produced. If these estimates are applicable to the entire finfish industry in Canada, then Canadian aquaculture operations contribute 956 tonnes of nitrogen and 204 tonnes of phosphorus per year to inland waters and 1 320 tonnes of nitrogen and 282 tonnes of phosphorus per year to coastal waters (Chambers et al. 2001). In comparison, a population of 100 000 that is served by secondary sewage treatment releases 365 tonnes of nitrogen and 25 tonnes of phosphorus per year in wastewater (Chambers et al. 2001).

## Forest management practices

Forests, particularly those occupying steep terrain and receiving abundant precipitation, are the source of much of the water that enters streams and lakes. Undisturbed forests cycle large quantities of nutrients, with very small losses to surface waters. Forest management practices, however, may increase streamwater concentrations of nutrients. Concentrations of dissolved nutrients, including nitrate, have been observed to increase (Chambers et al. 2001), although increases in nitrate were typically quite low and short-lived. Viewed from the perspective of a forest crop rotation of 60–100 years, the overall impact represents only small changes in nutrient inputs to aquatic systems. At the moment, however, there is insufficient information to generalize about the regional impacts of forestry practices on dissolved nutrients in streams.

## Atmospheric emissions, transport, and deposition

Nitrogen compounds are emitted to the atmosphere from a variety of sources, including industrial, agricultural, and transportation sources. Total emissions of nitrous oxide in 1995 were 98 000 tonnes as nitrogen, most of which (39%) was from agriculture, followed by transportation (32%) and industrial processes (24%). Other Canadian nitrogen oxide (i.e., nitric oxide and nitrogen dioxide) emissions the same year were 750 100 tonnes as nitrogen, primarily (52%) from transportation combustion sources. Agriculture was the largest contributor to ammonia emissions in 1995, with 92% of the total emissions (Table 7).

**Table 7: Canadian anthropogenic emissions of nitrogen compounds to the atmosphere, 1995**

| Sector | Emissions in 1995 (tonnes of nitrogen) $N_2O$ | Other $NO_x$ | $NH_3$ |
|---|---|---|---|
| Industrial combustion-related emissions | 3 000 | 86 000 | 400 |
| Industrial processes | 24 000 | 189 100 | 26 900 |
| Agriculture | 38 000 | | 570 000 |
| Transportation combustion | 31 000 | 393 000 | 4 200 |
| Forest fires | | 64 000 | |
| Non-industrial fuel combustion | | | 2 400 |
| Other sources | 2 000 | 18 000 | 18 900 |
| **Total** | **98 000** | **750 100** | **622 800** |

Source: Emissions data are from Environment Canada (1997a, 1999c), Vézina (1997), and Desjardins and Keng (1999).

Pollutants in the atmosphere may be transported by winds and global air circulation anywhere from a few tens of metres to thousands of kilometres beyond their point of release before being deposited to the Earth's surface. Deposition may be in wet form (e.g., rain or snow) or dry form (e.g., gravitational settling of particulate matter).

For nitrogen, the most abundant atmospheric compounds are nitrogen gas, gaseous nitric acid, particulate nitrate, and particulate ammonium sulphate and ammonium nitrate (Berden and Nilsson 1996). However, wet deposition of nitrate and ammonium is of most environmental significance, because of the contribution of nitrate to acid rain and of ammonium to decreased frost hardiness in trees. High rates of anthropogenic nitrogen deposition are a major concern in several parts of Canada; since 1977, Environment Canada and most Canadian provinces have monitored precipitation to determine wet deposition of acid-related substances (Ro et al. 1998). In Canada, atmospheric deposition arriving via long-distance transport supplies on average approximately 2.5 kilograms of nitrogen per hectare per year in the form of nitrate and ammonium, based on 1990s data (Ro et al. 1998). Ammonia is not a major air pollutant, but it is released on occasion from refrigeration systems, anhydrous ammonia production facilities, areas of intensive livestock management, and accidents during transportation (Teshow and Anderson 1989).

Phosphorus, in contrast, does not exist in a gaseous form. Phosphorus is present in the atmosphere, however, as particulates (dust and organic debris) and as water-soluble phosphate. Anthropogenic sources of phosphorus include releases from fertilizer application and from industrial sources that produce phosphorus products (e.g., phosphate rock processing and fertilizer production). The few studies of atmospheric phosphorus loadings that have been done have been undertaken as part of larger projects aimed at developing detailed phosphorus budgets for lakes. These studies suggest that atmospheric phosphorus accounts for only 1–6% of the total phosphorus budget in Canadian lakes (Ahl 1988).

# 5

# Selected Measures for Nutrient Management

A wide range of measures has been developed in Canada to help control nutrient inputs into the environment. Chapter 6 in Chambers et al. (2001) provides an in-depth examination of the various nutrient management initiatives by jurisdictions in Canada, including existing acts, regulations, guidelines, objectives, and voluntary initiatives that govern nutrients, fertilizers, and eutrophication. This chapter presents some selected key measures for managing nutrients in Canada.

## Municipal wastewater

Municipal wastewater has long been one of the major sources of nutrient loadings to aquatic ecosystems. However, the degree of municipal wastewater effluent treatment has improved. As a result, phosphorus contributions from municipal wastewater have declined since the early 1960s. Nonetheless, population growth has resulted in municipal wastewater remaining a significant source of nitrogen. The following are some solutions to further reduce nutrient loadings from municipal wastewater.

*Advanced phosphorus removal* is a well-established technology for treating wastewater. Directives are in place in some jurisdictions requiring municipal wastewater treatment plants that discharge to sensitive waters (e.g., municipalities along the Great Lakes) to employ advanced phosphorus removal.

*Phosphate recovery and recycling* in municipal wastewater treatment facilities is still at an early stage. Nonetheless, a number of research or demonstration installations are already running. Phosphorus is recovered, as phosphates, from municipal wastewater treatment plants and then recycled back into detergents and high-grade industrial products. Recycling of phosphates from wastewaters will also reduce sewage sludge volumes and ash production where sludges are incinerated and reduce chemicals used in sewage treatment works.

*Repair or replacement of sewage systems* ensures minimal infiltration during wet weather and reduces leakage and pollutant loadings. Conversion of combined sewer systems to separate systems or shunting of the most toxic first flush of stormwater into storage facilities/ponds for subsequent treatment at a municipal wastewater treatment plant prevents untreated sewage from entering surface waters. Sewer separation, however, is an extremely expensive way of solving the combined sewer problem, and it creates an additional stormwater problem in the process. To reduce separation costs, some local governments, such as the City of Vancouver, have implemented combined sewer separation programs on a replacement of aging infrastructure basis (Environment Canada 2001).

## Agriculture

Large-scale agricultural production without some nutrient losses to groundwater and surface waters and to the atmosphere is virtually impossible. However, some science-based solutions that can reduce agricultural nutrient losses are described below.

Most provinces in Canada have in place or are developing *nutrient management strategies or plans* for the production, storage, and use of agricultural nutrients on farms. These help to improve a farmer's ability to manage nutrients more effectively, with the ultimate aim of reducing overfertilization.

*Regional nutrient management plans* are beneficial in areas of intensive livestock production where the available agricultural land base is not sufficient for economic and environmentally safe application of manure. Animal and crop producers can cooperate in transporting and applying animal manure to farmland that is nutrient deficient. Through a network of farm operators, surplus manure can be transported from animal producers to crop farms so as to reduce the amount applied to concentrated areas and redistribute it over a broader agricultural base. Effective farm nutrient management can also include assessments as to the siting of intensive livestock operations or crops and the proportion of land that is set aside compared with the proportion of land that is intensively cropped.

Land application of manure and commercial fertilizers should be based on a balance between the requirements of the crops and the supply to the crops from the soil and from fertilization. Most provinces have *guidelines for manure application to soils*, which are typically based on nitrogen application rates, as nitrogen is usually the nutrient that limits crop growth. However, manure is rich in phosphorus relative to nitrogen, which means that application of manure to achieve a desirable level of nitrogen may result in an overabundance of phosphorus in the soil. Whereas most provinces have nitrogen guidelines for manure application to soil, Quebec has a phosphorus guideline for manure application to soil so as to protect surface water quality from phosphorus loadings due to phosphorus-saturated soil.

*Increasing nutrient retention by livestock* is another way of reducing nutrient additions to the environment. Livestock incorporate only 20–40% of the nitrogen and phosphorus originally present in the feed. Phytic acid is the main form of phosphorus in plants. Although cows have phytase, an enzyme that breaks down phytic acid, hogs and chickens do not. Technologies are now emerging for adding phytase and/or other supplements to livestock diets or to better match animal diet to requirements. Plant genetic approaches are also examining decreasing the phytic acid content of plants.

*Treatment of animal wastes* is not a new technology, but it has not been widely used. In areas of intensive livestock production, treatment of animal waste could be evaluated as an option for reducing the risk of manure contamination of surface water and groundwater.

*Nutrient best management practices* that are effective at reducing non-point source pollution are continually being developed. There is a growing research base on best management practices that are effective at reducing nutrient pollution (e.g., the development of recommended agricultural practices by the New Brunswick Department of Environment).

## Aquaculture operations

Only 20–30% of the nitrogen and phosphorus added to aquaculture operations is incorporated into fish biomass and removed at harvest; the other 70–80% of added nutrients is lost to the environment as metabolic waste, feces, and uneaten food fragments. *Improvements in feed quality* have reduced the feed coefficient (ratio of wet weight of feed used to wet weight of fish produced). New formulations should continue to focus on the development of more nutritionally balanced and digestible feed to reduce waste discharges from feeding.

Other options to minimize environmental impacts associated with nutrient loss in aquaculture operations include the following:

- *siting criteria* to lessen impacts from nutrient losses from cages and from waste discharges and to determine if a water body can support an aquaculture operation;
- *open water cage technology* so that cages can be placed away from restricted waters and shorelines;
- *criteria for the collection and treatment of wastewater*, particularly for cage operations in fresh water; and
- *good management practices* with respect to general site operations, waste disposal and garbage removal, and fish feeding practices.

# 6

# Information Gaps

This report has identified the effects of anthropogenic nutrients on Canadian ecosystems and the sources of these nutrients. It has documented deleterious changes in Canadian ecosystems as a result of nutrient loadings and the impacts of these changes on the quality of life of Canadians. However, the ability to assess changes in ecosystems in response to added nutrients is constrained by data limitations. These limitations can largely be divided into two categories: insufficient monitoring data on emissions and discharges and ambient conditions, and insufficient knowledge as to the effects of nutrient additions on ecosystem and human health.

## Insufficient monitoring data

Despite concerted attempts to define the status of Canadian ecosystems with respect to nutrients, data on sources and impacts become progressively less available as one moves from lakes to rivers/streams to wetlands to groundwater to coastal waters to forests. Topics requiring particular attention are:

- *industrial loadings to surface waters*: The availability of nitrogen and phosphorus data for industries not connected to municipal wastewater treatment plants is erratic; monitoring and reporting requirements vary among provinces and territories and among industrial sectors. Of the 2 130 industries in Canada with discharge permits, data on nutrient loadings were obtained for only 91 for nitrate, 142 for ammonium, and 191 for total phosphorus. Moreover, the data are not stored in any single database.
- *municipal wastewater treatment plant loadings to surface waters*: Data on nitrogen and phosphorus loadings are available for certain municipal wastewater treatment plants in Canada, but the data are not consistent in parameters measured or frequency of sampling. In addition, the data are not stored in any single database. The analysis of nutrient loadings from municipal wastewater treatment plants was achieved by applying per capita nutrient loading coefficients to the population served by the various levels of sewage treatment.
- *agricultural loadings to surface water and groundwater*: Although studies have been conducted at the scale of plots, fields, or small watersheds, regional or national estimates of nutrient loadings to surface waters and groundwater could not be calculated.

- *atmospheric deposition of phosphorus*: Although estimates of atmospheric deposition of nitrogen are available through a network of provincial and federal monitoring sites, similar data are not available for phosphorus, nor are estimates available for release from various sectors.
- *groundwater quality*: Well water survey programs are patchy across the country. Some wells are already above or close to guidelines for nitrate and bacteria. Little information is available on ammonia and phosphorus in groundwater.
- *fish kills from accidental spills/discharges of nutrient-related compounds*: Currently, reporting is on a voluntary basis only.
- *climate change scenarios*: Study of the potential impacts of climate change on nutrient loadings and related measures is required to manage loadings.

## Effects of nutrient addition on ecosystem and human health

Nutrient management is a persisting environmental issue, as nutrients, unlike toxic chemicals, for example, cannot be eliminated by reformulation or discontinuance. Additional research is required to understand the effects of added nutrients on Canadian ecosystems. Areas requiring particular attention are:

- the role of nutrients in inducing blue-green algal blooms and toxin production;
- the role of nutrients in causing taste and odour problems in drinking water supplies;
- interactions of nutrients with organic contaminants and their effects on aquatic food webs;
- effects of sewage and industrial wastewater plumes on aquatic life during periods of ice cover (i.e., limited mixing of the plume and cold water temperatures);
- fate and transport of nutrients within different ecosystems (wetlands, coastal waters, forests, rivers, and lakes) and effects on biota;
- effects of long-term (decades) nutrient loading on aquatic and terrestrial ecosystems, including water and sediment/soil quality and food webs;
- effects of forest management practices on nutrient loss from forests to aquatic ecosystems;
- cumulative effects on the aquatic environment from the combination of several nutrient sources all operating within a region; and
- the relationship between nutrient concentrations and aquatic plant biomass, particularly for streams and coastal waters, and the level of aquatic plant biomass that begins to impair beneficial uses of streams for the preservation of aesthetics or recreation and protection of aquatic life.

# 7 Conclusions

The objectives identified for the science assessment upon which this report is based were "*to determine whether or not nutrients in general are causing negative environmental effects; whether only certain nutrients, rather than nutrients as a class, are problematic; and whether those effects are limited … to water or to entire ecosystems, including wildlife.*" Based upon these objectives, the following conclusions are drawn:

➤ ***Nutrients released to the environment from human activities are impairing the health of certain ecosystems, contributing to quality of life concerns for Canadians, and, on occasion, endangering the health of humans.*** Nitrogen and phosphorus loadings from human activities have:

- contributed to the eutrophication of some rivers, lakes, and wetlands in Canada;
- caused fish and amphibian lethality;
- contributed to the acidification of soils and lakes in southern Ontario and Quebec;
- resulted in incipient nitrogen saturation in some forested watersheds;
- led to elevated risks to human health through increased frequency and spatial extent of toxic algal blooms in Canadian lakes and coastal waters;
- increased the frequency and spatial extent to which the drinking water guideline for nitrate has been exceeded in groundwater across Canada;
- contributed to quality of life concerns for Canadians through water use impairments and aesthetic concerns related to water supplies; and
- increased the economic burden to Canadians as a result of the need for treatment, monitoring, and remediation of contaminated water.

➤ ***Nutrient impacts on particular environments in Canada tend to be associated with certain nutrient forms.***

- Most inland waters in Canada are intrinsically phosphorus limited. Consequently, addition of bioavailable phosphorus (i.e., phosphorus in the form of phosphate) has accelerated eutrophication of certain rivers, lakes, and wetlands in Canada.

- In contrast to inland waters, widespread effects of anthropogenic nutrients have generally been minimized in coastal environments. Localized problems caused by point or non-point source nutrient addition are, however, evident, and one particular concern is the role of nitrogen in contributing to the development of toxic algal blooms in coastal waters.
- Nitrogen is also an issue with respect to groundwater, where leaching has increased the frequency and spatial extent to which the drinking water guideline for nitrate has been exceeded in groundwater across Canada.
- Concerns about nutrients in the atmosphere relate largely to the role of nitrogen in urban smog production and, in the form of nitrous oxide, a potent greenhouse gas, in global warming. These issues were not dealt with in any detail in the science assessment (Chambers et al. 2001) or in this report.

At present, environmental problems caused by excessive nutrients are less severe in Canada than in many countries with a longer history of settlement and agricultural production. This is in part due to protective measures implemented by governments in the last 30 years, such as permit limits for regulating wastewater discharges from industrial and municipal sewage treatment plants, and the refinement of measures for addressing excessive nutrient loadings as new information and technology became available. Nonetheless, while successes have been realized, environmental and human health problems related to nutrients are evident across Canada.

However, Canada is in the position of being able to deal with nutrient pollution before it is overwhelming. Science-based solutions are available, and new technologies are emerging that can assist in further reducing nutrient additions to the environment. In many jurisdictions, there has been a shift from “end-of-pipe” responses to a more preventative or proactive approach. This shift is a result of a growing tendency towards a broad ecosystem approach to environmental protection and sustainable development.

Nutrient-related research and monitoring continue to be needed to ensure that decision-making is based upon sound science. The gains achieved by improved wastewater treatment and other control measures must not be reversed by relaxation of standards or by failure to keep pace with population growth, and environmental policy should continue to emphasize integrating the best and most advanced science into practical solutions.

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# Glossary of Selected Terms[1]

A

**algal bloom**: See *bloom*.

**ammonia-nitrogen**: Nitrogen in the form of ammonia ($NH_3$). See also *nitrogen fixation*.

**anoxia**: The absence of oxygen, which is necessary to sustain most life. In *aquatic* ecosystems, this refers to the absence of dissolved oxygen in water.

**aquatic**: Pertains to both freshwater and marine ecosystems.

B

**biologically available**: The physical or chemical form of a substance that can be directly used by an organism.

**bloom** (also known as **algal bloom**): Rapid growth of certain algal constituents of plankton in and on a body of water that is so heavy as to colour the water. The rapid growth can be fuelled by enrichment of *nutrients*, such as nitrogen and phosphorus.

C

**contamination**: Introduction of any undesirable foreign substance — physical, chemical, or biological — into an ecosystem. Does not imply an effect (see *pollution*). Usually refers to the introduction of human-made substances.

**cumulative effect:** The effect on the environment that results from the incremental impact of an action when added to other past, present, and reasonably foreseeable future actions.

D

**denitrify**: To reduce (nitrates) to nitrites, ammonia, and free nitrogen, as in soil by microorganisms (Infoplease, Internet URL www.infoplease.com/index.html).

**drainage basin**: See *watershed*.

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[1] Except where otherwise noted, terms are from or modified from *The state of Canada's environment — 1996*. Ottawa: Government of Canada, Environment Canada (1996). Terms in italics are defined elsewhere in the Glossary.

### E

**effluent**: A liquid waste material that is a by-product of human activities (e.g., municipal wastewater or liquid industrial waste), which may be discharged into bodies of water.

**eutrophic:** Pertaining to a body of fresh water that is rich in *nutrients* and hence in living organisms. See also *trophic, trophic level*, and *trophic status*.

**eutrophication** (also known as **nutrient enrichment**): The process of overfertilization of a body of water by *nutrients* that produce more organic matter than the self-purification reactions can overcome. Eutrophication can be a natural process, or it can be accelerated by an increase in nutrient loadings to a water body by human activities. See also *trophic*, *trophic level*, and *trophic status*.

### F

**food chain**: A food relationship in an ecosystem in which energy and *nutrients* are transferred through a series of organisms by each stage feeding on the preceding one and providing food for the succeeding stage. Each stage of a food chain is known as a *trophic level*. The first trophic level consists of the green plants that can undertake photosynthesis, thereby obtaining their energy from the sun. See also *food web*.

**food web:** A complex intermeshing of individual *food chains* in an ecosystem.

### G

**groundwater**: Water occurring below the ground surface, which may supply water to wells and springs. Groundwater occupies pores, cavities, cracks, and other spaces in bedrock and unconsolidated surface materials.

### H

**habitat**: The place or type of site where plant, animal, or microorganism populations normally occur. The concept of habitat includes the particular characteristics of that place, such as climate and the availability of water and other life requisites (e.g., soil *nutrients* for plants and suitable food and shelter for animals), which make it especially well suited to meet the life cycle needs of the particular wildlife.

### L

**leaching**: Washing out of soluble substances by water passing down through soil. Leaching occurs when more water falls on the soil than is lost by evaporation from the surface. Rainwater running through the soil dissolves mineral *nutrients* and other substances and carries them via *groundwater* into water bodies.

**loading**: Total mass of contaminants to a water body or to the land surface over a specified time (e.g., tonnes per year of nitrogen or phosphorus).

### M

**macronutrient**: An element, such as nitrogen, phosphorus, or potassium, essential in large quantities for plant growth.

**macrophyte**: A plant, especially an aquatic plant, large enough to be visible to the naked eye (Infoplease, Internet URL www.infoplease.com/index.html).

**mesotrophic**: See *trophic status*.

**monitoring**: The process of checking, observing, or keeping track of something for a specified period of time or at specified intervals.

**N**

**nitrogen fixation**: Conversion of gaseous (atmospheric) nitrogen ($N_2$) to compounds such as ammonia ($NH_3$). Carried out in ecosystems mainly by bacteria of the genus *Rhizobium*. See also *ammonia-nitrogen*.

**nitrogen oxides (NOx)**: A group of gases released by fossil fuel combustion, forest fires, lightning, and decaying vegetation. Nitrogen dioxide ($NO_2$), a reddish-brown gas with an irritating odour, is one of the key ingredients in smog. Nitrous oxide ($N_2O$) is a greenhouse gas whose principal source is agricultural soil in a degraded state.

**non-point source**: Source of pollution in which pollutants are discharged over a widespread area or from a number of small inputs rather than from distinct, identifiable sources. Examples include eroding croplands, urban and suburban lands, and logged forestlands. See also *point source*.

**nutrient**: Any element or compound that an organism must take in from its environment because it cannot produce as much as it needs. As pollutants, any substance or group of substances (e.g., nitrogen or phosphorus compounds) that, if added to water in sufficient quantities, provides nourishment that promotes the growth of *aquatic* vegetation in those waters to such densities as to degrade or alter the quality of those waters.

**nutrient enrichment**: See *eutrophication*.

**O**

**oligotrophic**: See *trophic status*.

**organic compounds**: Compounds based on carbon and usually also containing hydrogen, with or without oxygen, nitrogen, or other elements. Organic originally meant "of plant or animal origin," and it is still sometimes used in this way. For example, manure and sewage contain organic compounds of animal and plant origin. However, now that organic compounds are routinely created by people, the word "organic" is also used to refer to synthetic organic compounds, such as synthetic fertilizers.

**organic matter**: Plant, animal, or microorganism matter, either living or dead.

**P**

**phytoplankton**: Microscopic *aquatic* vegetative life; plant portion of the *plankton*; the plant community in marine and freshwater situations that floats free in the water and contains many species of algae and diatoms.

**plankton**: Collective noun for organisms that drift around in water because they cannot swim against currents in the water. See also *phytoplankton* and *zooplankton*.

**point source:** A source of pollution that is distinct and identifiable. Includes outfall pipes from municipal sewage treatment plants and industrial plants. See also *non-point source*.

**pollution:** The release by humans, directly or indirectly, of substances or energy into ecosystems that results or is likely to result in such deleterious effects as to harm living resources and life, be hazardous to human health, hinder human activities, impair the quality of the ecological resources, or reduce amenities.

**primary wastewater treatment**: First step in sewage treatment to remove large solid objects by screens (filters) and sediment and organic matter in settling chambers. See also *secondary wastewater treatment* and *tertiary wastewater treatment*.

## S

**salmonid**: Pertaining to fish of the family Salmonidae, including the salmons, trouts, and chars.

**secondary wastewater treatment**: After *primary wastewater treatment*, removal of biodegradable organic matter from sewage using bacteria and other microorganisms, inactivated sludge, or trickle filters. Also removes some of the phosphorus (30%) and nitrate (50%). See also *tertiary wastewater treatment*.

## T

**tertiary wastewater treatment**: Removal of nitrates, phosphates, organochlorine compounds, salts, acids, metals, and toxic *organic compounds* after *secondary wastewater treatment*. See also *primary wastewater treatment*.

**toxic**: Pertains to any substance if it is entering or may enter the environment in a quantity or concentration or under conditions having or that may have an immediate or long-term effect on the environment (including living organisms within it) or constituting or that may constitute a danger to human life or health.

**toxicity**: The inherent potential or capacity of a material to cause adverse effects in a living organism.

**trophic**: Relating to processes of energy and *nutrient* transfer from one or more organisms to others in an ecosystem. See also *eutrophic, trophic level*, and *trophic status*.

**trophic level**: Functional classification of organisms in a community according to feeding relationships; the first trophic level includes green plants, the second level includes herbivores, and so on. See also *eutrophic, trophic,* and *trophic status*.

**trophic status**: A measure of the biological productivity in a body of water. *Aquatic* ecosystems are characterized as oligotrophic (low productivity), mesotrophic (medium productivity), or *eutrophic* (high productivity). See also *trophic* and *trophic level*.

**turbid**: Refers to water that is cloudy or murky as a result of suspended sediment. Water may become turbid as a result of soil erosion, from injections of effluents containing particulate matter, or through the churning up of bottom sediments (e.g., via boat traffic in a body of water).

**turbidity**: The state of being *turbid*.

## W

**watershed**: An area of land that drains naturally into a stream or other waterway.

## Z

**zooplankton**: Microscopic animals that move passively in *aquatic* ecosystems. See also *phytoplankton* and *plankton*.

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